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Energy management for hybrid electric vehicles using rule based strategy and PI control tuned by particle swarming optimization algorithm

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ABSTRACT

Recently, hybrid electric vehicles are increasingly being used to replace conventional vehicles. In this paper, a control methodology is designed that can reduce fuel consumption and improve the vehicle's dynamic response. As the control unit based on this methodology consists of two levels, the first depends on the application of a rule-based strategy for energy management between the main components of the vehicle, and this strategy is based on a set of rules that are activated according to parameters such as vehicle speed and the battery state of charge (SOC) that control the activation/deactivation of the internal combustion engine (ICE), motor, and generator. This level also makes ICE operate at operation points with high efficiency, which is represented by the optimal operating line (OOL). The second level is called the low control level, and it consists of two proportional-integral (PI) controllers used to control the speed of each ICE and the motor to obtain the appropriate torque for both of them to drive the vehicle properly. The particle swarming optimization (PSO) algorithm is utilized to tune the parameters of the PI controllers. The obtained results have effectively minimized fuel consumption and improved the performance of the vehicle.

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1. INTRODUCTION

The increase in the consumption of fossil fuels by conventional vehicles, which leads to an increase in emissions of carbon dioxide, as transport emissions have been classified as the second-largest source of emissions after industrial emissions [1]. For this reason, hybrid electric vehicles (HEV) are considered an alternative solution to conventional vehicles. Where HEVs reduce fossil fuel consumption by making the internal combustion engine (ICE) operate at more efficient operation points, in addition to capturing the kinetic energy resulting from deceleration of the vehicle or through regenerative braking and this energy is stored in the battery for later use in the propulsion of the vehicle [2]. The HEVs rely on an energy management strategy to accomplish this task, and the energy management strategies for HEVs are divided into two main categories: a rule-based strategy also known as logic threshold control strategies and an optimization strategy [3].

In this article, a rule-based strategy is adopted as the energy management strategy for a series-parallel HEV. The rules of this rules-based strategy are built on parameters the battery charge status (SOC), ICE speed, and vehicle speed. Where this strategy is based on meeting the power required by the driver by splitting the power between each of the ICE, motor, and generator for the purpose of making the ICE operates at more efficient operating points as well as maintaining the SOC in a certain range [4]. Figure 1 shows the power flow between the main components of a series-parallel HEV.

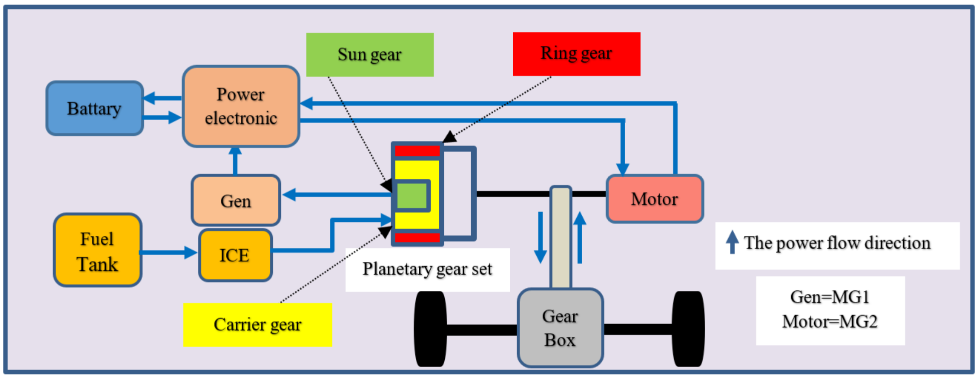

Figure 1. The series-parallel hybrid electric vehicle

In study [5], a model of a series-parallel HEV was built that operates with a controller unit depends on the rule-based strategy. The rule-based strategy in this unit depends on the actual vehicle speed, the vehicle's desired speed, and the SOC of the batteries. To reduce fuel consumption, the ICE is operated with high-efficiency operating points. For this purpose, was used the optimal operation line (OOL) to find the ICE torque at a certain ICE speed by the 1-D lookup table. As for [6], where the model of the series-parallel HEV contains dual planetary gear sets, and the control unit of this model uses the rule-based strategy. This strategy is based on the idea of energy flow according to the operating mode and SOC, where the energy required for the vehicle is calculated and how it is provided from the energy sources in the vehicle according to this strategy. In addition, in study [7] rule-based strategy is used to drive a model of a series-parallel HEV, where this strategy works to provide the torque required by the vehicle through a distribution between the ICE and motor or by the motor only, depending on the load conditions and SOC. Similarly, the study [8] also explains how to build a control unit to drive a series-parallel HEV using a rule-based strategy whereby this unit decides the vehicle's propulsion mechanism either using the electric motor only or by the ICE and the motor together, these decisions are made depending on the inputs of this unit where the torque required by the vehicle and SOC are considered as inputs to this unit. This article also demonstrates getting the ICE to operate at higher efficiency points as this is done by making the torque points greater than 20% of the maximum torque at the set speed, as well as avoiding running the ICE at low speed.

It has been proven in the literature that fuel consumption can be further improved by making the ICE operates at highly efficient operating points, in addition to build a rule-based strategy that controls the start/stop of the ICE at the appropriate times and not starting it when it is not needed. The contributions of our work can be understood by achieving improved fuel consumption by building a control unit working with a rule-based strategy that controls the timely ICE start/stop as well as making the ICE operates within the range OOL, which represents the ICE operating points with high efficiency. Therefore, a control unit will be set up to manage the operation of the HEV. This unit consists of two levels, the first level, the supervisory control level (SCL), works to improve fuel consumption by achieving the basic conditions for operating the ICE in highly efficient operating points, and these points are represented in the OOL, as well as avoiding running the ICE at low speeds. The second level is the low control level (LCL) and consists of the proportional-integral (PI)-controller units to control the speed of both the ICE and the motor, where the parameters of these units are tuned by using the practical swarm optimization algorithm (PSO) algorithm. The results obtained were encouraging when using these two levels of control to reduce fuel consumption on the one hand and obtain a good response to the system on the other.

This article has been organized, the section 2 describes the dynamic equations of the vehicle in addition to describing the main components of the powertrain of the vehicle which are the ICE, motor, generator, and planetary gear set (PGS). While the control unit and its two levels will be explained in addition to describing the operation modes of the HEV, the state of charge SOC of the battery, and the rules of the rule-based control strategy in section 3. As for section 4, it presents the simulation results for of the series-parallel HEV model in terms of fuel consumption and on the one hand, it shows the system's response to commands. Finally, section 5 concludes with the main findings of this research paper.

2. MODELLING OF HYBRID VEHICLE SYSTEM

In this article, a vehicle of series-parallel type was selected and represented by the forward hybrid vehicle model is used for studying and developing a control management strategy. The model of hybrid vehicles includes the drive cycle, hybrid powertrain, vehicle dynamics, and control unit subsystem models. We will discuss the important subsystem models:

2.1. Vehicle dynamics

To drive a vehicle, an appropriate traction force for the vehicle must be found and this force equals to the summation of the vehicle's resistive forces as it is being driven. These forces are aerodynamic resistance, rolling resistance, gradient resistance, and inertial force. So the vehicle traction equation is represented as (1) [9]:

$$F_T = F_A + F_R + F_G + F_I \tag{1}$$

where the F_T, F_A, F_R, F_G and F_I are the traction force, aerodynamic resistance, rolling resistance, gradient resistance, and an inertial force respectively.

$$F_A = 0.5\rho C_d A_f V^2 \tag{2}$$

$$F_R = C_t \, mg \cos\theta \tag{3}$$

$$F_G = mg \sin\theta \tag{4}$$

$$F_I = m\frac{dV}{dt} \tag{5}$$

Vehicle parameters of the HEV model used in this article are shown in Table 1.

Table 1. Vehicle parameters of the HEV

Abbreviation	Definition	Value (Units)
A_f	Vehicle frontal area	2.16 m2
g	Gravitational constant	9.81 m/s2
ρ	Air density	1.18 kg/m2
C_d	Drag coefficient	0.26
m	Total mass of the vehicle	1200 Kg
V	Speed of the vehicle	m/s
θ	The slope of the road	0 radians
C_t	Wheel rolling friction coefficient	0.01

2.2. Powertrain of the series-parallel HEV

2.2.1. Internal combustion engine

The ICE is represented in MATLAB by a generic engine block from the Simulink library, it has the specifications in Table 2 [10]. The ICE is connected to the carrier gear of the planetary gear set. Because of this connection, the ICE's power is used to propel the vehicle and to charge the batteries [7]. In addition, the speed of ICE affects the selection of generator specifications, because they are connected by the planetary gear set, and this may lead to the generator being operated at higher speeds than the designed speed when the appropriate speed specifications are not chosen for the generator.

Table 1. ICE parameters

Parameter	Value
Maximum power	11400 W
The speed at maximum power	5000 rpm
Maximum speed	6000 rpm

The control unit gives commands to ON/OFF the ICE and also sets the torque value of the ICE to operate which ensures that the ICE operates within the OOL range [11], [12]. This torque value is chosen based on the ICE speed which in turn is an entry into the 1-D lookup table. This 1-D lookup table contains values for the ICE's speed and the corresponding torques that represent the OOL range. The output of this 1-D lookup table is the torque value of the ICE which ensures that it operates within the OOL range, the optimal operation line OOL is shown in Figure 2.

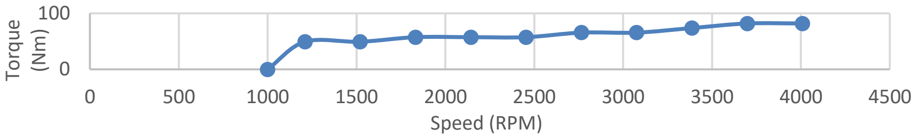

Figure 2. OOL of the ICE

2.2.2. Actuators (motor/generator)

The electric generator and motor (MG1/MG2) are represented in MATLAB/Simulink by a simplified permanent magnet synchronous motor (PMSM) drive block that represents a servomotor model with closed-loop torque control, the parameters of the MG1 and MG2 model are shown in Table 3. The MG1 and MG2 are connected to the sun gear and the ring gear of the planetary gear set respectively. The MG1 operates as an electric generator to charge the batteries or to give electric power to the MG2. The MG1 also acts as a self-starter for the ICE. While the main function of MG2 is to propel the vehicle, and the MG2 also acts as an electric generator when the vehicle's speed is decreasing or when the braking mode is activated. The control unit manages the operation of the MG1 and MG2.

Table 3. Electric motor/generator parameters

Parameter	Motor	Generator
Vector of rotational speeds (rpm)	[1200 2000 3000 4000 6000 6500 1000]	[0 1200 2000 3000 4000 10000 15000]
Vector of maximum torque values (N*m)	[400 400 250 150 110 90 0 0]	[400 400 250 150 110 0 0]

2.2.3. Planetary gear set

The series-parallel HEV contains a power split device is represented by the planetary gear set (PGS), which consists of three components (nodes) are the sun gear, carrier gear, and ring gear. Where the main components of HEV, which are the generator, ICE, and driveshaft are connected to the sun gear, carrier gear, and ring gear respectively. The power generated in the ICE is transmitted through PGS to each of the generator and driveshaft. The power of the sun gear is transmitted to the generator, where it is transformed into electrical power that is stored in the batteries. This path of power is called the electrical path. While the power of the ring gear is transmitted to the drive shaft, this power path is called the mechanical path [13]. Because of the existence are the PGS and connection of the MG2 with the drive shaft, the vehicle is allowed to use the power of the ICE and MG2 to propel the vehicle. The angular velocity of the PGS is organized according to (6):

$$(N_S + N_R)\ \omega_{ICE} = N_R\ \omega_{MG2} + N_S\ \omega_{MG1} \tag{1}$$

where the angular velocity of the motor and the torque for both the ring node and sun node are defined by:

$$\omega_{MG1} = \frac{i_f}{r_w} V \tag{2}$$

$$T_R = \frac{N_R}{N_R+N_S} * T_C \tag{3}$$

$$T_S = \frac{N_S}{N_R+N_S} * T_C \tag{4}$$

In (6)-(9), N_R and N_S are the number of teeth of the sun and ring gears; ω_{ICE}, ω_{MG2}, and ω_{MG1} are the ICE, motor, and generator angular speed; i_f is final transmission gear ratio; r_w is the wheel radius; V is the vehicle speed; T_R, T_R and T_S are the torque of the ring gear, carrier gear, and sun gear respectively. T_C and T_S are equal to ICE torque and generator torque respectively. The values of the N_R and N_S in this HEV model are 78 and 30 respectively.

3. CONTROL UNIT

The control strategies in HEVs are the brain of the vehicle, and these control strategies manage the division, distribution, and capture of energy from among the energy sources present in the vehicle. Where the energy sources in HEVs are chemical energy contained in fossil fuels, and electric energy stored in batteries. In addition to the kinetic potential energy resulting from the deceleration or braking of the vehicle [4]. The control unit in this HEV model consists of two-level control. The first is the supervisory control level and the second is the low control level as shown in Figure 3.

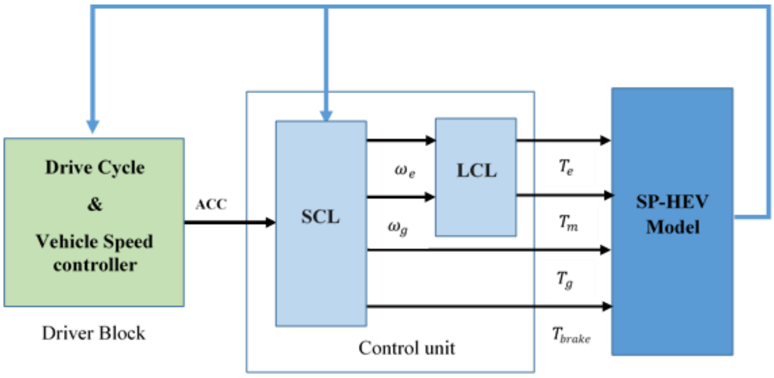

Figure 3. The control system of the HEV

3.1. The supervisory control levels

The main objective of this control level is to obtain maximum fuel consumption economy and thus minimize emissions harmful to the environment. This is done by controlling the ICE ON/OFF, avoiding the ICE working at low speeds, and the most important thing is to make the ICE operate with high efficiency operating points at a certain speed. The highly efficient operating points are obtained of the ICE by compensating the difference torques between the current operating point and the highly efficient operating points at a certain speed by split power between the ICE and the motor or electric generator to compensate for the difference. In addition, these strategies, also use the kinetic energy resulting from deceleration or braking of the vehicle and store it in the form of electrical energy in the batteries [14]. As mentioned earlier there are two main types of energy management strategies, and in this article, the rule-based strategy was relied on [8]. Before explaining the performance of the rule-based strategy, HEV operating models and SOC cases will be explained.

3.1.1. HEV operation modes

The operation modes are divided, depending on the contribution of each ICE and motor whether to propel the vehicle or to charge the batteries into two main models:

a. Single-mode: in this mode, one of these machines, either the ICE or electric motor, contributes to propel the vehicle or charging the batteries. This mode includes the following: i) *Motor_Mode*: the electric motor runs alone to propel the vehicle; ii) *Generator_Mode*: the electric motor works as a generator that converts the kinetic energy a result of the deceleration and braking of the vehicle into electrical energy and stores this energy in the batteries; and iii) *Charging_Mode*: ICE is operated to charge the batteries; in which case the vehicle is stationary.
b. Combined-mode: in this mode, the electric motor contributes to assisting in the propulsion of the vehicle, while ICE works in the propulsion of the vehicle in addition to charging the batteries when there is an excess of energy. This mode includes the following: i) *Single source_mode (SS_mode)*: ICE is operated for generating power that is greater than or equal to the power required by the vehicle. This power has two paths, one for the drivetrain, and the other for the electric generator, where the electric power transmits from the generator to the electric motor to contribute to the vehicle's propulsion. If the electric power of the generator is greater than the electric power is consumed in the motor, so the remaining power is sent to the batteries to charge and ii) *Double source_mode (DS_mode)*: each of the ICE and electric motor are operated for propulsion of the vehicle, where the power produced in two paths by ICE is less than the required power of the vehicle, and the difference is compensated by the electric power drawn from the batteries, and which is sent to the electric motor to provide the required power of the vehicle.

3.1.2. The battery state of charge

It is the ratio of the current energy of a battery to the total energy of the battery or a measure of the remaining energy in the battery. SOC units are represented by percentage points such as 0%=empty of energy; 100%=full of energy. Where SOC is calculated by (10) [15]:

$$SOC = \frac{Q_{batt} - \int_{t_o}^{t} I_{batt}(\tau)d\tau}{Q_{batt}} * 100\% \quad (5)$$

where I_{batt} and Q_{batt} are the battery current and the total capacity of the battery respectively. SOC in this strategy is divided into five levels are: i) SOC<10%: The ICE only operates to charge the battery; ii) 10%<SOC<30%: The ICE operates to charge the battery and drive the vehicle, while the motor is not allowed to run only to drive the vehicle at low speed because the motor takes its power from the ICE by the generator; iii) 30%<SOC<80%: The ICE operates only to charge the battery and to drive the vehicle, while the motor is allowed to run only to drive the vehicle; iv) 80%<SOC<90%: The ICE is not allowed to charge the battery at this level. The battery is charged through regenerative braking; and v) SOC>90%: It is not allowed to charge the battery at this level. The units of SOC between SOC_{min}=25% and SOC_{max}=80% are considered to be the best values for battery operation because they reduce premature battery aging [16], [8].

3.1.3. Rule-based control strategy

The rule-based control strategy is a method that relies on a set of rules that are used to determine the appropriate operation mode among the vehicle's operation modes. These rules are set by heuristics or mathematical models. This is an easy-to-implement and computationally fast strategy because it is implemented by lookup tables [6], [7]. The supervisory level contains entries that are processed by the rules in the rule-based strategy to obtain logical outputs to control the on or off of each of the ICE, motor, and generator. The entries include the vehicle speed, SOC, brake signal, and ICE speed. While the outputs are represented by a logical state (0 or 1) and include (*Motor_Enable*: indicates the activation of the electric motor when it is equal to 1), (*Gen_ Enable*: indicates the activation of the generator when it is equal to 1) and (*ICE_Enable*: indicates the activation of the ICE when it is equal to 1). Here we will discuss how to determine the operation mode of the vehicle as shown:

a. When the brakes are energized (Brake>0), it means that the vehicle is in (*Generator_mode*).
b. When the vehicle speed is less than 45 km/h and SOC is greater than the SOC_{min} then the vehicle here operates at (*Motor_mode*).
c. If the vehicle stops (vehicle speed=0) and SOC is less than SOC_{min} this makes the vehicle enter in (*Charging_mode*). In this model, the ICE is started to charge the batteries by the electric generator, and here the ICE must operate within the range of the OOL, and planetary gear set (PGS) acts as a speed coupler because the ring is fixed in this state. This mode continues to work when there is no change in the inputs until the arrival of ($SOC>SOC_{min}$).
d. When the vehicle speed exceeds 45 km/h, the vehicle enters the combined mode. This means the ICE is turned on (the ICE motor must be operating in the OOL range) and power flows to two paths, one of which transmits power to the drivetrain by PGS is the mechanical path, while the second is an electric path where the power is transmitted from the ICE to the generator by PGS and then from the generator to the motor or to the batteries. The vehicle enters (*SS_mode*) when the power generated by the ICE is equal to the power required for the vehicle, and this indicates that power in an electric path is transmitted from the ICE to the generator and from it to the motor only. The vehicle also remains in (*SS_mode*) when the power generated by the ICE is greater than the power required for the vehicle, and this indicates that the power in an electric path is transmitted from the ICE to the generator and from it to the motor and batteries together, where the excess power is stored as electrical energy in the batteries. While if the ICE power is less than the power required for the vehicle, the lack of power is compensated by the electric energy in the batteries, which is transferred to prepare the motor, and here the vehicle enters with (*DS_mode*). In another case in combined mode (*DS_mode*), when the vehicle is accelerating, the control unit turns off the generator and activates both the ICE and the motor to provide the required power.

3.2. Low control level based on PI controllers

Low control level has been designed by the PI-controller. This level contains two units from the PI-controller to control the speed for each ICE and motor. The PI-controller is a feedback control loop that processes the error signal [17], and the error signal is the difference between the output of a system (PV) and the set point (SP), as shown in Figure 4. It provides a faster response time than I-only control due to the addition of proportional action. PI control stops the system from fluctuating, and it is also able to return the system to its set point. The PI-controller in mathematical form is illustrated in (11) [10], [18]:

$$C(t) = K_P \times e(t) + K_I \int e(\tau)d\tau \quad (6)$$

where, $C(t), K_I, K_P$ and $e(t)$ are the output of the controller, proportional gain constant, integral gain constant, and error signal respectively [19]. The error signal is given by:

$$e(t) = SP - PV \quad (7)$$

In this article, the parameters of PI-controllers for each motor and ICE will be tuned by the PSO [20], [21]. The PSO described in the area of artificial intelligence (AI), is an algorithm inspired by nature, derived from the social behavior of organisms, such as flocks of birds, fish education, and human social relationships [22], [23]. The basic principle of calculating PSO is by having a large population which is called a swarm and every single population is called a particle. Each particle represents a potential solution to the problem [24], [25]. These particles will move in the search space according to some basic formulas. The movement of each particle in the search space is directed through, firstly the position indicated by its best position resulting from its own experience, and secondly by the best position of the entire swarm, as shown in Figure 5. The movements of the swarm in each stage are at the optimal positions that were found in the previous iteration, and thus the swarm search will be in smaller areas than the previous areas, which leads to the approach of the swarm to the optimal solution [26]. In this article, the PI controller uses the PSO algorithm to tune its parameters, since P and I are used in the PI controller therefore each particle in the search space has two dimensions. The velocity and the position of the particle are updated after each iteration by the (13) and (14) [27]–[29]:

$$v_I^{k+1} = wv_I^k + c_1r_1\left[P_{best,I}^k - x_I^k\right] + c_2r_2\left[G_{best}^k - x_I^k\right] \quad (8)$$

$$x_I^{k+1} = x_I^k + v_I^{k+1} \quad (9)$$

where, k: iterations pointer, $v_I^k = (v_{i1}^k, v_{i2}^k, \dots, v_{id}^k, \dots, v_{in}^k)$, v_I^k is the velocity of the i-th particle at k-th iteration, v_{id}^k is the velocity of the i-th particle at d-th dimension and k-th iteration, $x_I^k = (x_{i1}^k, x_{i2}^k, \dots, x_{id}^k \dots, x_{in}^k)$, x_I^k is the position of the i-th particle at k-th iteration, x_{id}^k is the position of the i-th particle at d-th dimension and k-th iteration, $P_{best,I}^k$: Personal best position of the i-th particle at k-th iteration, G_{best}^k is the global best position of the particle in the swarm at k-th iteration, c_1, c_2 is acceleration factors (positive constant), or Cognitive and social parameters respectively, r_1, r_2 is random coefficients, where the value of these coefficients is between 0-1, and w: Inertia weight. It is used to control the previous velocity.

For the swarm has N particles and the best position of the particle and the best position of the swarm are updated after each iteration by using (15) and (16) respectively Whereas f in these equations denotes the cost function. The cost function is a mathematical equation for measuring and evaluating the performance of a particle in a swarm, and in this article, the integral absolute error (IAE) was used as the cost function which is one of the most common performance parameters used in a proportional-integral–differential (PID) controller, the IAE formula is shown in (17).

$$P_{best,I}^{k+1} = \begin{cases} P_{best,I}^k & if \quad f(x_I^{k+1}) > f(P_{best,I}^k) \\ x_I^{k+1} & if \quad f(x_I^{k+1}) \le f(P_{best,I}^k) \end{cases} \quad (15)$$

$$f(G_{best}^{k+1}) = Min(f(G_{best}^k), f(P_{best,1}^{k+1}), f(P_{best,2}^{k+1}), \dots, f(P_{best,N}^{k+1})) \quad (16)$$

$$IAE = \int_0^T |r(t) - y(t)|dt = \int_0^T |e(t)|dt \quad (17)$$

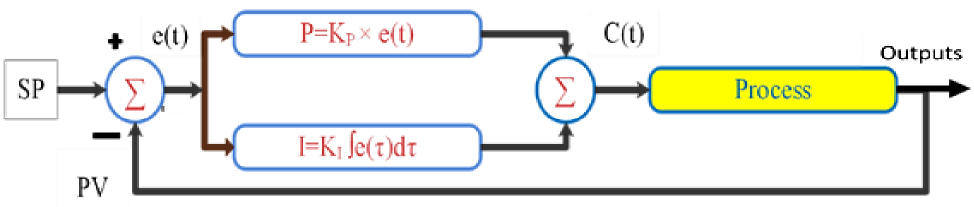

Figure 4. PI-controller unit

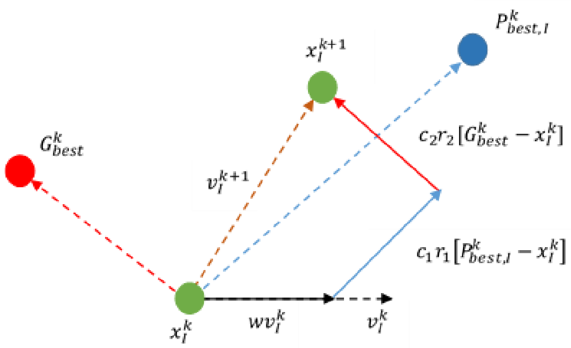

Figure 5. The velocity vector and the position vector for PSO

4. SIMULATION RESULTS

The simulation was carried out on a series-parallel HEV model by MATLAB/Simulink (2019 b) environment. Where the new European driving cycle (NEDC standards) was used as the driving cycle in this simulation, the NEDC consists of two parts: the urban driving cycle (UDC) repeat 4 times, during the period from 0 seconds to 780 seconds and has a top speed of 50 km/h, and extra urban driving cycle (EUDC) is plotted from 780 seconds to 1,180 seconds and has a top speed of 120 km/h, as shown in Figure 6. The driving cycle block contains PI-controller to handle the difference between the required speed of the driving cycle and the actual vehicle speed. The signal generated by this unit is sent to the control unit.

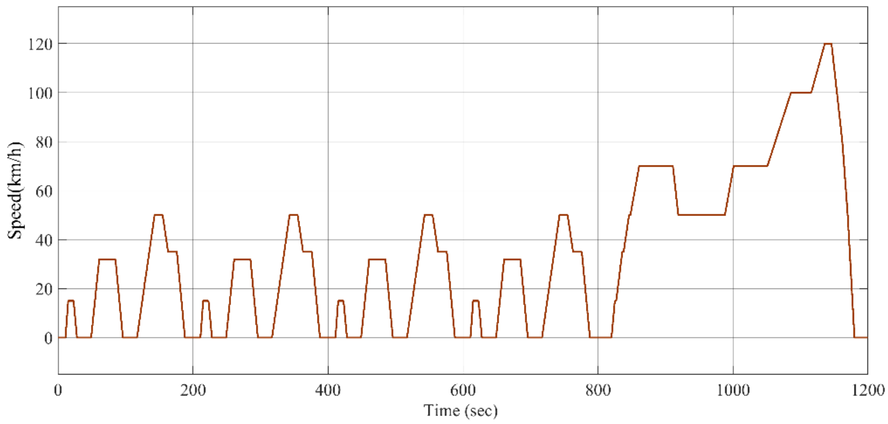

Figure 6. New European driving cycle (NEDC standards*)*

In this simulation, the control unit of the HEV, which had two levels of control, is studied and analyzed. The functions of the supervisory control level are to determine the torque value of the generator to make the ICE operate within the OOL range, evaluate the value of the reference speed of the ICE and motor, check the operating conditions in the *Motor_mode*, and finally manage the ON/OFF of both the ICE, motor, and generator. To make the ICE operate within the range of the OOL, this is done by setting the torque values of the ICE from among the torque values in the range of the OOL. This value is extracted by the 1-D lookup table block, which contains the points of OOL, where the input of this block is the required ICE speed and the output of this block is the torque value of the ICE, which is belonging to the range of the OOL. The extracted ICE torque value is used to obtain the required generator torque through (9), and this generator torque value is calculated using the supervisory control level. As for the PI-controller of the ICE to handle the difference between the required speed of the ICE and the actual speed. The required ICE speed is determined by matching the signal generated in the drive cycle to the ICE speed using the 1-D lookup table block in MATLAB/Simulink, and also the PI-controller of the motor is handling the difference between the required motor speed and the actual motor speed. The required motor speed is determined by using (7), where V in this equation is the required speed in the drive cycle. While the function of checking operating conditions in *Motor_mode* is to compare the power required by the vehicle at the speed under 45 km/h with the maximum power of the motor at a certain speed. If the power of the motor is greater than the power required by the vehicle and the vehicle speed is under 45 km/h, then the output of this unit is (*EV_Mode=1*) or otherwise, it is (*EV_Mode=0*), and this function determines whether the motor can operate alone at the *Motor_mode*.

The last and important function of the supervisory control level is the ON/OFF management of the ICE, motor, and generator. This is done by applying the rules of the rule-based strategy to assign the vehicle's operating mode, as each mode contains a specific mechanism is done by turning on-off each of the ICE, motor, and generator. The unit that contains this function is called the ON/OFF management unit, it has the entries: vehicle speed, SOC, *EV_Mode*, ICE speed, and braking. Whereas its outputs are the *ICE-Enable*, *Mot-Enable*, and *Gen_Enable*. Figures 7 and 8 represent the state of the inputs and outputs of the ON/OFF management unit in this simulation.

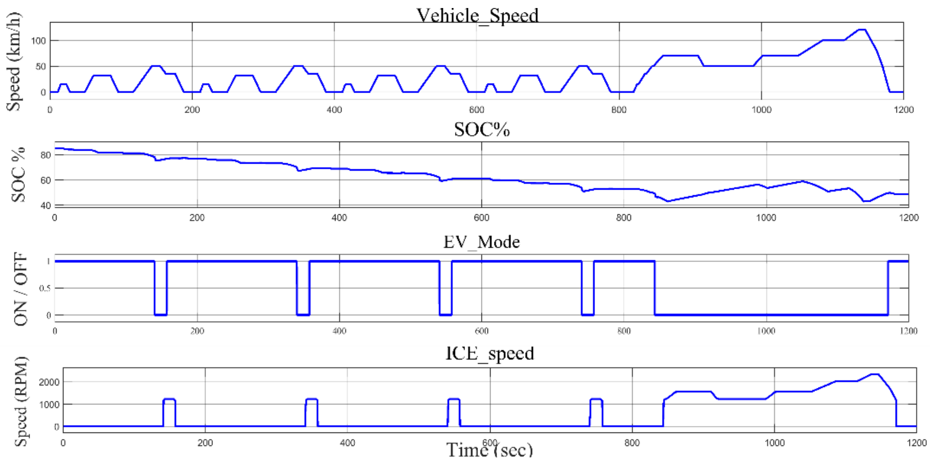

Figure 7. The inputs of the ON/OFF management unit

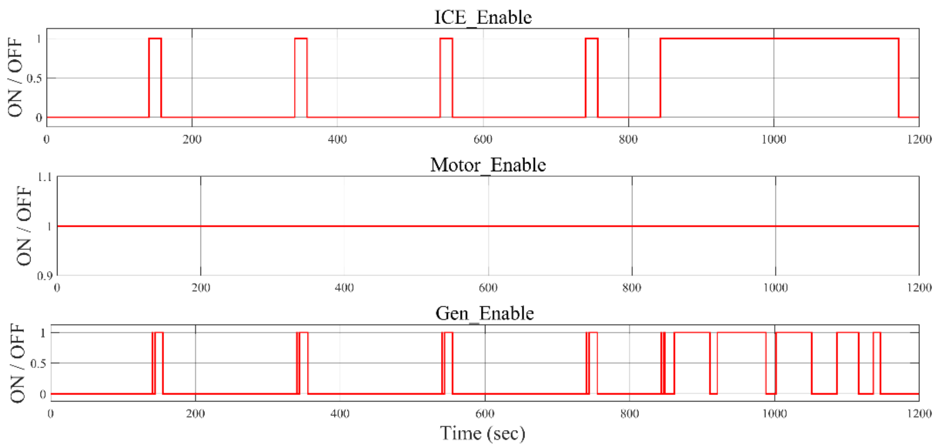

Figure 8. The outputs of the ON/OFF management unit

During the NEDC the vehicle traveled a distance of 10.9 km. Which the vehicle traveled a distance of 2.461 km and it was operating in the single-mode. While the vehicle was operating in the combined-mode in the remaining distance. We find this clear by watching the outputs of the ON/OFF management unit. We notice that the motor operates throughout the trip, while the ICE operates at certain stages, and these stages are in which the vehicle operates in the combined-mode, and what remains represents the single-mode by operating the motor only, whether to propel the vehicle or re-capture kinetic energy when the decelerated vehicle. The fuel consumed in the vehicle is measured using 2-D lookup tables, where the values of the torque and rotational speed of the ICE represent the two dimensions of this table. The 2-D lookup table also contains the values of the fuel mass flow rate [g/s] for each value of the torque and rotational speed of the

ICE. Where the amount of fuel consumed is calculated by the integration process for the fuel mass flow rate [g/s] during the driving period. In this way, the fuel consumption of the HEV model was measured during the simulation, as the vehicle consumed about 0.4702 liters of fuel during this trip. It is noted that SOC during the driving cycle passed through different stages, including the stages of discharging and charging. Whereas, the value of the SOC at the start of the simulation is 85% and SOC during the drive cycle was higher than the lower bound the SOC_{min}. In this simulation, PSO was used to tune the parameters of PI-controller units for the ICE and motor. Where the PSO parameters used for the PI controller for both the ICE and motor are shown in Table 4.

Figure 9 compares the actual ICE speed using the PI-controller, where its parameters were tuned by using the Simulink discrete PID controller block and the PID tuner tool. The Simulink PID controller design model is used for this purpose [30], [10], and their values were (Kp=0.02, Ki=0.01), and the actual ICE speed using the PI-controller whose parameters were tuned by the PSO algorithm and its values were (Kp=0.06, Ki=0.06). Where the drawing also contains the required speed of the motor. We note when using the PSO algorithm, there was an improvement in response and enhancement of the dynamic performance of the system, as well as a slight improvement in terms of fuel consumption. Where the vehicle consumed about 0.4701 litter fuel during this trip when using the PSO algorithm to tune PI-controller parameters. Figure 10 compares the actual motor speeds resulting from the use of the PI-controller, whose parameters are tuned by the two methods mentioned above, where the values of the parameters of the first method were (K_p=500 and K_I=300), while the values of the parameters by using the PSO algorithm were (K_p=864.8098 and K_I=869.8186). We also notice an improvement in the response of the system.

Table 4. The PSO parameters of the PI-controller for the ICE and motor

	Pop size	iteration	c_1	c_2	Search space	w
ICE	20	20	1.5	1.5	[0.01,0.06]	0.729
Motor	20	20	1.5	1.5	[820,875]	0.729

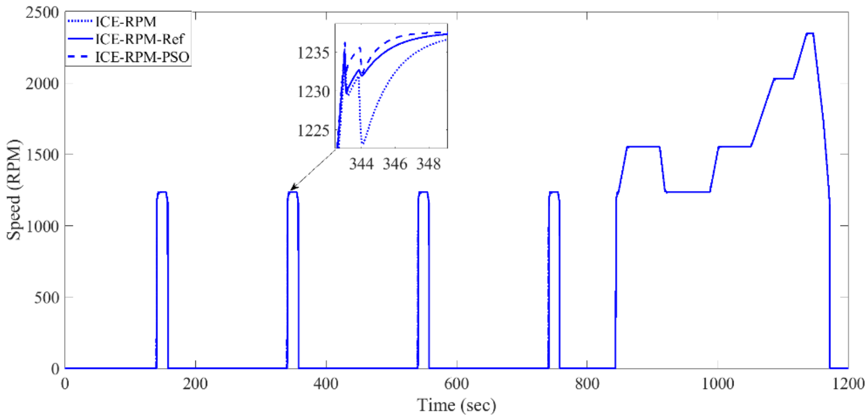

Figure 9. Speed controller signals of the ICE

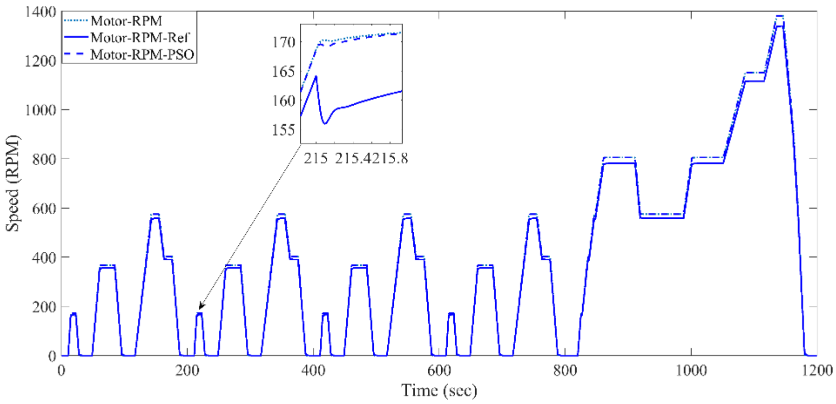

Figure 10. Speed controller signals of the motor

Table 5 demonstrates a comparison between the fuel consumption of the model of the HEV when the ON/OFF management unit is activated and when it is deactivated during the drive of the HEV model by the NEDC. It was noted that the fuel in the case of deactivated the ON/OFF management unit is consumed more. Where the amount of fuel consumed in the case of deactivation is approximately 1.38 times the fuel consumed in the case of activating the unit. The reason is due to the ICE's contribution over the cycle to propel and feed the motor with energy through the generator.

Table 5. The fuel consumption of the HEV

ON/OFF management unit	Activate	Deactivate
Total fuel used (Litter)	0.4702	0.6507

5. CONCLUSION

The control unit was built in a series-parallel HEV model that works to meet the energy required by dividing the energy between the sources in the HEV, which reduces fuel consumption and improves the performance of the vehicle. This unit has two levels of control, firstly, the SCL which is built based on the rule-based strategy that is easy to implement and computationally fast. Additionally, to make the ICE operates within the range of the OOL. It is assumed that the ICE does not operate at low efficiency operating points as this leads to fuel consumption. Therefore, it must be made to operate at highly efficient operating points represented by the OOL and operates only when needed. The appropriate HEV operation modes are chosen to achieve the required power from the vehicle as well as reduce fuel consumption, for example, the vehicle should only rely on the motor to drive when the required power of the vehicle is less than the maximum motor power and the SOC is within the permissible. The second level is the LCL, which is composed of two PI-controller units for each ICE and motor, and to obtain a convenient approach to tune the parameters of the PI controller, the PSO algorithm was used, which works effectively to improve the overall performance in terms of fuel consumption and system response.

REFERENCES

[1] H.-Y. Hwang and J.-S. Chen, "Optimized fuel economy control of power-split hybrid electric vehicle with particle swarm optimization," *Energies*, vol. 13, no. 9, May 2020, doi: 10.3390/en13092278.

[2] S. Verma *et al.*, "A comprehensive review on energy storage in hybrid electric vehicle," *Journal of Traffic and Transportation Engineering (English Edition)*, vol. 8, no. 5, pp. 621–637, Oct. 2021, doi: 10.1016/j.jtte.2021.09.001.

[3] J. P. Torreglosa, P. Garcia-Triviño, D. Vera, and D. A. López-García, "Analyzing the improvements of energy management systems for hybrid electric vehicles using a systematic literature review: how far are these controls from rule-based controls used in commercial vehicles?," *Applied Sciences*, vol. 10, no. 23, Dec. 2020, doi: 10.3390/app10238744.

[4] F. Zhang, L. Wang, S. Coskun, H. Pang, Y. Cui, and J. Xi, "Energy management strategies for hybrid electric vehicles: Review, classification, comparison, and outlook," *Energies*, vol. 13, no. 13, 2020, doi: 10.3390/en13133352.

[5] A. B. Jadhav, "Optimal energy management for forward-looking serial-parallel hybrid electric vehicle using rule-based control strategy," Western Michigan University, 2019.

[6] Y. Zou *et al.*, "Modeling and energy management strategy research of a power-split hybrid electric vehicle," *Advances in Mechanical Engineering*, vol. 12, no. 10, Oct. 2020, doi: 10.1177/1687814020962624.

[7] D. Biswas, S. Sengupta, D. Mitra, and S. Mukhopadhyay, "Improved energy management strategy of hybrid electric vehicles with varying terrain," *IFAC-PapersOnLine*, vol. 51, no. 31, pp. 618–625, 2018, doi: 10.1016/j.ifacol.2018.10.147.

[8] D. Fernández, "Model building and energy efficient control of a series-parallel plug-in hybrid electric vehicle," Chalmers University of Technology, 2016.

[9] B. Varga, A. Sagoian, and F. Mariasiu, "Prediction of electric vehicle range: a comprehensive review of current issues and challenges," *Energies*, vol. 12, no. 5, Mar. 2019, doi: 10.3390/en12050946.

[10] K. Baltaci, "Development of a modular dual engine hybrid electric vehicle simulation model," University of Northern Iowa, 2012.

[11] D. Jelaska, M. Perkušić, S. Podrug, and V. Tvrdić, "A novel approach to energy management strategy for hybrid electric vehicles," *SAE International Journal of Commercial Vehicles*, vol. 14, no. 2, Feb. 2021, doi: 10.4271/02-14-02-0010.

[12] Y. Wang, X. Jiao, Z. Sun, and P. Li, "Energy management strategy in consideration of battery health for PHEV via stochastic control and particle swarm optimization algorithm," *Energies*, vol. 10, no. 11. 2017, doi: 10.3390/en10111894.

[13] S. B. Kanap, "Modeling and simulation with optimal gear ratio for a forward-looking, velocity-driven, power-split hybrid electric vehicle," Western Michigan University, 2019.

[14] R. R. Gugale, M. Student, and T. U. Kaiserslautern, "Rule based energy management strategy for a parallel mild hybrid electric vehicle," *Seminar Electromobilty Ss 2017*, no. July, pp. 0–6, 2018

[15] P. Poramapojana and B. Chen, "Minimizing HEV fuel consumption using model predictive control," in *Proceedings of 2012 8th IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications, MESA 2012*, 2012, pp. 148–153, doi: 10.1109/MESA.2012.6275553.

[16] A. E. Trippe, R. Arunachala, T. Massier, A. Jossen, and T. Hamacher, "Charging optimization of battery electric vehicles including cycle battery aging," in *IEEE PES Innovative Smart Grid Technologies Conference Europe*, 2015, pp. 1–6, doi: 10.1109/ISGTEurope.2014.7028735.

[17] G.-G. Jin and Y.-D. Son, "Design of a nonlinear PID controller and tuning rules for first-order plus time delay models," *Studies in Informatics and Control*, vol. 28, no. 2, pp. 157–166, Jul. 2019, doi: 10.24846/v28i2y201904.

[18] R. P. Borase, D. K. Maghade, S. Y. Sondkar, and S. N. Pawar, “A review of PID control, tuning methods and applications,” *International Journal of Dynamics and Control*, vol. 9, no. 2, pp. 818–827, Jun. 2021, doi: 10.1007/s40435-020-00665-4.
[19] A. Ali and M. Rashid, “Design PI controller for tank level in industrial process,” *Iraqi Journal for Electrical and Electronic Engineering*, vol. 18, no. 1, pp. 82–92, Jun. 2022, doi: 10.37917/ijeee.18.1.10.
[20] A. Al-Mayyahi, W. Wang, and P. Birch, “Path tracking of autonomous ground vehicle based on fractional order PID controller optimized by PSO,” in *SAMI 2015-IEEE 13th International Symposium on Applied Machine Intelligence and Informatics, Proceedings*, 2015, pp. 109–114., doi: 10.1109/SAMI.2015.7061857.
[21] A. K. Kashyap and D. R. Parhi, “Particle swarm optimization aided PID gait controller design for a humanoid robot,” *ISA Transactions*, vol. 114, pp. 306–330, Aug. 2021, doi: 10.1016/j.isatra.2020.12.033.
[22] A. Chitra, P. Sanjeevikumar, J. B. Holm-Nielsen, and S. Himavathi, *Artificial intelligent techniques for electric and hybrid electric vehicles*. Wiley-Scrivener, 2020., doi: 10.1002/9781119682035.
[23] M. I. M. Zakki, M. N. M. Hussain, and N. Seroji, “Implementation of particle swarm optimization for tuning of PID controller in arduino nano for solar MPPT system,” *International Journal of Electrical and Electronic Systems Research (JEESR)*, vol. 13, no. 11, pp. 1–8, 2018
[24] A. K. Vincent and R. Nersisson, “Particle swarm optimization based PID controller tuning for level control of two tank system,” *IOP Conference Series: Materials Science and Engineering*, vol. 263, no. 5, Nov. 2017, doi: 10.1088/1757-899X/263/5/052001.
[25] M. Mohammed, A. Ali, and M. Rashid, “Fuzzy petri net controller for quadrotor system using particle swam optimization,” *Iraqi Journal for Electrical and Electronic Engineering*, vol. 11, no. 1, pp. 132–144, Jun. 2015, doi: 10.37917/ijeee.11.1.14.
[26] O. Adel, Y. Berkani, T. Nabil, and T. Rekioua, “Speed control and performance analysis of PMSM using particle swarm optimization speed control and performance analysis of PMSM using particle swarm optimization,” *International Conference on Applied and Industrial Diagnostics*, 2017.
[27] N. Kumar, N. Pal, P. Kumar, and A. Kumari, “Impact of different inertia weight functions on particle swarm optimization algorithm to resolve economic load dispatch problems,” in *2018 4th International Conference on Recent Advances in Information Technology (RAIT)*, Mar. 2018, pp. 1–5., doi: 10.1109/RAIT.2018.8389065.
[28] P. B. de Moura Oliveira, J. D. Hedengren, and E. J. S. Pires, “Swarm-based design of proportional integral and derivative controllers using a compromise cost function: An arduino temperature laboratory case study,” *Algorithms*, vol. 13, no. 12, 2020, doi: 10.3390/a13120315.
[29] B. N. A. Samed, A. A. Aldair, and A. Al-Mayyahi, “Robust trajectory tracking control and obstacles avoidance algorithm for quadrotor unmanned aerial vehicle,” *Journal of Electrical Engineering and Technology*, vol. 15, no. 2, pp. 855–868, Mar. 2020, doi: 10.1007/s42835-020-00350-8.
[30] A. Turevskiy, “PID controller design for a DC motor,” *Mathworks*. 2022.

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