Development of a Simulink model for a parallel HEV using Rule Base Strategy to reduce fuel consumption

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HEVs are vehicles that uses two or more different power converters, combining the output of these converters for the propulsion purpose of the vehicle by either serial, parallel or combined connection. HEV research is rising rapidly, because of the disadvantages of pure ICE vehicles (environmental and fuel consumption). Although EVs are a promising solution, HEVs provide a bridge platform between the two technologies (pure ICE and EV). EMS (Energy Management strategy) is a critical parameter in HEV. The chosen EMS will affect the efficiency and fuel consumption. Different EMS are available now such as Rule based and optimization strategies, when using the Rule Base strategy, the aim is to find the optimal driving mode for NEDC and FTP driving cycles to increase the efficiency. For this purpose, the simulation software Simulink/ MATLAB is used along with QSS toolbox, With a novel code for the controller. From the simulation results comparing with a conventional version of the same vehicle, there is a fuel save of 19.3% for NEDC cycle for 11 KM and 26.4% for FTP-75 for 17.7 K.M cycle while the SOC (state of charge) at the end of each driving cycle was the same as the SOC at the beginning.

***Index Terms*—HEV, fuel consumption, Rule Based, Simulink,**

I. INTRODUCTION

Over the past few years, the interest of renewable energy has become significant. There are many reasons for this. Due to high nature disaster like for example the flood in Rheinland-Pfalz and Nordrhein-Westfalen in this summer and environmental pollution, the government discusses stricter law against cars which run on fossil fuels. At the moment, the technology of batteries for electric cars is not fully developed to run for a long distance with one complete charge. As a result, hybrid cars become a temporary solution. In the city it is possible to run the car at low speed with an electric motor. This leads to low noises, low fuel consumption and less exhaust emissions. When the charge is empty or when the car is on high speed, the combustion engine will drive the vehicle. Hence, it is possible to drive the car for a long distance.

As much research of past show, the efficiency is depending on the right controller strategy. One paper which sums up the Control Algorithm is [5]. This shows the significance of the controller. In [6] and [7] a rule-based approach is used to design a controller. The efficiency of the system combines with the simplicity of the implementation show satisfactory results. Therefore, a rule-based strategy is applied in this paper.

To get a low fuel consumption, the hybrid car has to know when the optimal point to switch between the internal consumption motor and the electrical motor is. Furthermore, it must know when the correct time to charge or uncharged the battery is. For the question of switching into the different modes, the energy management comes into play. The aim of the energy management system is to minimize the fuel consumption for the given driving cycles FET and NEDC

In this paper, the software MATLAB/Simulink was used with the Quasi-Statistics Simulink tool. It was investigated how the average consumption of a mild parallel hybrid vehicle can be minimized under a controller based on rule base strategy. It was used here because of its simplicity. Here, the consumption of the combustion engine was optimized for the driving cycles of NEDC and FET 75.

The paper has the following structure. In part II, fundamental theory will be established for different types of hybrid vehicles and also for energy management strategy. In part III the results of the model and the code are listed and explained. Followed by conclusion and future work in part IV.

II. FUNDAMENTALS

A. Types of hybrid vehicles

They are different types of hybrid vehicles: serial hybrid, parallel hybrid and combination hybrid. The definition is determined by their construction. Regardless of the type, they all have a battery, electric motor, and an internal combustion engine.

1) Serial hybrid vehicle

An electric motor is used to drive the vehicle. The combustion engine driving the generator is used to supply power to the electric motor [5].

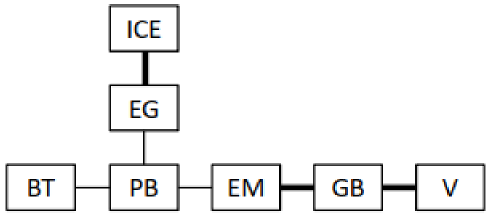

Figure 1 Architecture of a series hybrid electric vehicle [3]

The combustion engine and the generator are mechanically connected to each other, as the electric motor as with the gearbox and the vehicle. The electrical and mechanical connections are connected via the Power Link. Since the combustion engine and the electric motor are not mechanically coupled, the combustion engine can be operated mainly at the optimum operating point [3].

2) *Parallel hybrid vehicle*

In this architecture, the electric motor and the combustion engine work together on one drive shaft. Therefore, the vehicle can be moved either with the combustion engine, with the electric motor or with both engines together [5].

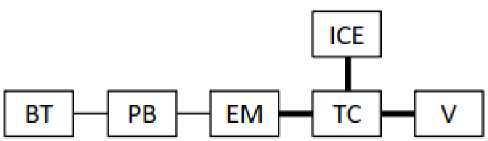

Figure 2 Architecture of a parallel hybrid electric vehicle [3]

Here the combustion engine and the electric motor are connected to a drive shaft via a torque coupler. An electric motor can work as a motor and as a generator. Since the combustion engine is connected to the gearbox, the combustion engine cannot always be operated at the optimum point [3].

3) *Combined hybrid vehicle*

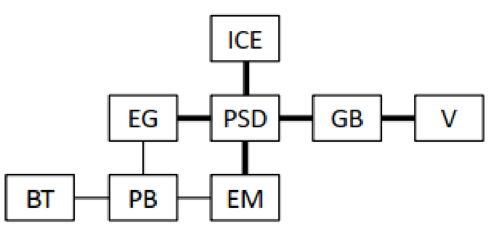

Figure 3 Architecture of a combined hybrid electric vehicle [3]

Here, the generator, combustion engine, power, transmission, electric motor and the vehicle are mechanically connected to each other. The generator works as a motor for the start/stop function and as a generator while charging the battery. The electric motor also works as a generator for recuperation [3].

B. *Energy Management Strategy*

In order to execute the respective mode, an energy management strategy is required. Here, the heuristic energy management strategy was used, which depends on many vehicle variables. Furthermore, rules have to be defined that are user dependent. These rules can be based on the efficiency of the combustion engine, so that it is always operated at the optimal point when in use. Another possibility is the battery charge. If the battery is for example below a defined value, the preference is placed more on charging and if the charge is sufficient, the focus is placed on the use of the electric motor. Two approaches are available for implementation. These are map-based method and rule based method [4]. Here the focus is on rule base for more details the reader is referred to [4]. In the rule-based implementation, there are state and condition. The state is changed depending on the conditions [4].

Rule base strategy

For the rule base method, a finite state machine is needed. See figure 4. After a condition is met, the state is exited and changed to the next state. In order to fulfil this condition, however, the states are strongly coupled to threshold values. In the case of parallel hybrid vehicle, the states are start/stop, electric drive, regeneration, load point shift and conventional driving [4].

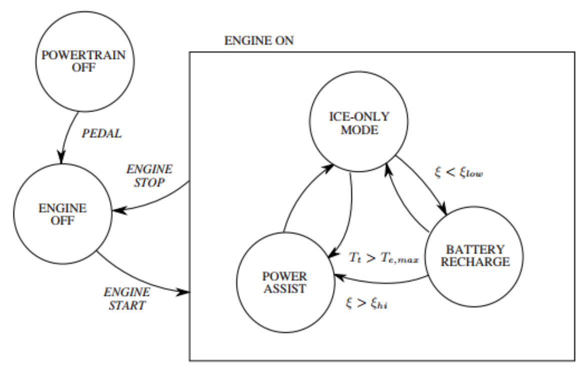

Figure 4 A finite-state machine illustrating a rule-based, heuristic energy management strategy [4]

The torque split ratio u is the ratio between the torque of the electric motor and that of the Manuel gearbox. These variable changes depending on the driving mode.

$$u = \frac{T_{EM}}{T_{MGB}}$$

1) *Start/stop method*

Vehicles which have this technology on board will switch off the internal combustion engine when the car is for example at a traffic jam. This system will significantly reduce the fuel consumption which arises due to idling. This system will not work when the battery charge is too low or the clutch in manual gearbox is pressed [3].

Resulting values:

$$T_{EM} = T_{MGB}\ , T_{CE} = 0 \text{ and } u{=}0$$

2) Electric Driving

A combustion engine always has poor efficiency at low load. Therefore, it is always recommended to switch off the combustion engine at low loads and to operate the electric motor in areas with low loads. For middle load ranges, it is beneficial to run the electric motor in generator mode and to increase the load of the combustion engine so it is efficient [3]. In order to run this mode, certain conditions must be met. There must be sufficient battery capacity to power the vehicle with the electric motor. Furthermore, the required torque must be available from the electric motor, otherwise the combustion engine must intervene [3].
Resulting values:

$$T_{EM} = T_{MGB}\ , T_{CE} = 0 \text{ and } u = 1$$

3) Regeneration

Instead of the kinetic energy that is dissipated in heat during braking, this kinetic energy is converted into electrical energy and stored in the battery. This happens when the electric motor works in generator mode during the braking phase. This also brakes the car [3].
Resulting values:

For $T_{MGB} < 0$

$$u = \frac{T_{EM}}{T_{MGB}} = \min\left(\frac{-T_{EM.max}(\omega_{EM}) + |\theta_{EM} d\omega_{EM}| + \varepsilon}{T_{MGB}}, 1\right)$$

4) Load Point Shifting

As described in electric driving, the efficiency of the combustion engine depends on the load. The load range of the combustion engine can be controlled by clever switching of the electric motor as a generator or as a motor. This allows the combustion engine to be operated in the optimum range. The combustion engine is supported when the electric motor is operated as a motor. This lowers the load point shift. Conversely, when the electric motor operates as a generator, the combustion engine is loaded more and thus the load point shift is increased [3].
Resulting values:

In motor mode $T_{MGB} \geq T_{MGB,th}$

$$u = \frac{T_{EM}}{T_{MGB}} = \min\left(\frac{T_{EM.max}(\omega_{EM}) - |\theta_{EM} d\omega_{EM}| - \varepsilon}{T_{MGB}}, 1\right) \quad (1)$$

and in generator mode $T_{MGB} \leq T_{MGB,th}$

$$u = \frac{T_{EM}}{T_{MGB}} = \max\left(\frac{-T_{EM.max}(\omega_{EM}) + |\theta_{EM} d\omega_{EM}| + \varepsilon}{T_{MGB}}, 1\right) \quad (2)$$

5) Conventional Driving

Here, the vehicle is driven without a function of the electric motor. The vehicle is a conventional vehicle [3].
Resulting values:

$$T_{CE} > 0 \text{ and } u = 0$$

C. Case study subject

Figure 5 shows the architecture of the simulation model consists of the blocks driving cycle, vehicle, manual gearbox, control unit, combustion engine, electric motor, battery and two displays. In general, the driving cycle contains information at a known length of the cycle about the speed and the corresponding number of gears at that speed. Thus, the driving cycle describes how the vehicle behaves on a given route and how the driver drives the vehicle. Two driving cycles were used in this simulation. The New European Cycle and the US Federal Test Procedure (FT-75). The New European Cycle is 11 km long, the duration is 1180s, the average speed is 33.6 km/h, and the maximum speed is 120 km/h. The New European Cycle is a test cycle. Furthermore, the Federal Test Procedure is 17.77km long with a duration of 1874s. The average speed is 34.1 km/h and the maximum speed is 91.2 km/h.

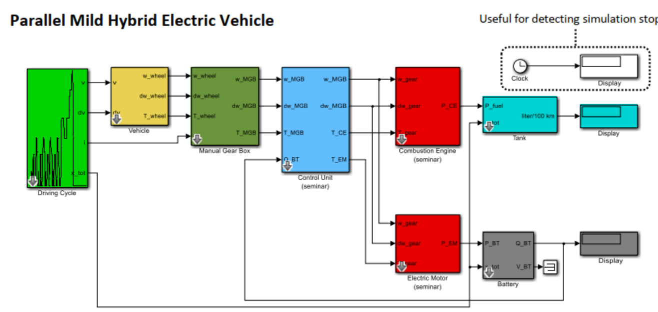

Figure 5 Simulation model blocks

The targeted vehicle is a Mercedes A160 with the following specification

Table 1 vehicle parameter of the study subject

Vehicle Parameter	Value/Type
Vehicle Model	MB A 170 CDI (W168, 1115 kg)
Engine	Diesel, 60 kW, 187 Nm, 4200 rpm, 1698 cm
Motor	PMS,12 kW, 60 Nm, 7639 rpm
Battery	Li-ion, 16.38 kW, 0.468 kWh, 46.8 V, 13 m
Gearbox	Manual (5 Speed)
Clutch	Friction type (CE and EM)

III. RESULTS

The used Simulink model is made of connected blocks, each block represents a functional system of the vehicle and connected with arrows represent input and output signals. Each of these models has a subsystem to represent the signal rout and input/output relationship. The most important system to control the fuel consumption is the control unit block here is where power distribution and split ratio is decided and takes place. those decisions are based on the controller where the code is written. this model is shown in the following fig 6.

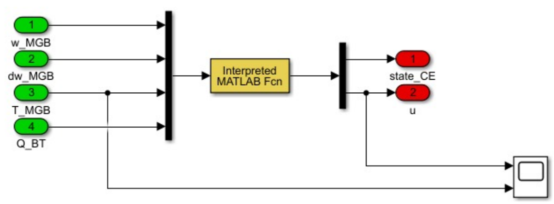

Figure 6 Block diagram of Controller

The proposed strategy in this paper is Rule based, since it is straight forward and easy to manipulate and modify. The results were also satisfying using this strategy with a fuel save up to 26%. The key factor in this strategy is thresholds setting. This strategy is based on rules that will be set and decide the driving mode accordingly. Those rules are based on parameters or thresholds that decide start and end of each mode. One obstacle we faced is the overlap of the values. When tow conditions are met at once, this will result in an execution error and also unexpected results. The other key point to watch is variable declaration, those variables need to be global in order to be used by all other systems. The structure of the code is based on state machine. First the thresholds and parameters are set, then cases. Part of this code for the first case is:

```
switch (next_mode)

  case 1

    State
      state_CE = 0;
      u = 1;
      prev_mode = 1;

      % Switch Conditions
      if SOC <= SOC_in
        next_mode = 4;
       elseif T_MGB < T_ED_max
        next_mode = 3;
       elseif T_MGB >= T_ED_max
        next_mode = 2;
      end
```

The controller uses 4 inputs and results 2 outputs, shown in this table:

Table 2 inputs and outputs of the controller

Parameter	Input	Output
Flywheel angular velocity	w_MGB	-
flywheel angular acceleration	dw_MGB	-
flywheel torque	T_MGB	-
charge of battery (C)	Q_BT	-
Combustion engine state	-	state_CE
Torque split ratio	-	u

Also, the used parameters and their values are listed in the following table:

Table 3 values and thresholds to define driving mode

Parameter	Value	Definition
theta_EM	0.1	motor inertia
T_MGB_th	55	torque threshold - lower bound for entering LPS in generator mode
T_MGB_th2	90	torque threshold - lower bound for entering LPS in motor mode
T_ED_max	38	max Torque for Electric Driving
epsilon	0.01	Epsilon (design parameter)
u_LPS_max	0.33	maximum torque-split for LPS
SOC_in	14	SOC for entering Charge mode
SOC_out	38	SOC for quitting Charging mode

The rules of the strategy are listed in the following table, where it shows for each driving mode the output of the controller which controls power torque distribution. It also lists the conditions where to enter this particular driving mode in respect to the thresholds and inputs. And, when those conditions are met, it will direct the controller to which next driving mode should go next. The code starts with an *isempty* statement to ensure it always start from the first case.

Table 4 the state machine details and parameteres

Case	**Mode**	**Output**		**Exit condition**	
1	Start stop	State_CE=0		**Condition**	**Go to**
				SOC <= SOC_in	4
		U=1		T_MGB < T_ED_max	3
				T_MGB >= T_ED_max	2
2	LPS	State_CE=1		**Condition**	**Go to**
		Condition	**U**	T_MGB < 0	5
		T_MGB >= T_MGB_th2 (Motor Mode)	(1)	SOC <= SOC_in	4
		T_MGB > 0 && T_MGB < T_MGB_th (Generator Mode)	(2)	T_MGB < T_ED_max	3
		else	0	T_MGB == 0	1
3	Electric Drive	State_CE=0		**Condition**	**Go to**
				SOC <= SOC_in	4
		U=1		T_MGB < 0	5
				T_MGB >= T_ED_max	2
4	Charging	State_CE=1		**Condition**	**Go to**
		Condition	**U**	SOC >= SOC_out	2
		T_MGB>0 && T_MGB <= T_MGB_th2 (Generator Mode)	(2)	T_MGB < 0	5
		Else	0	-	-
5	Braking	State_CE=0		**Condition**	**Go to**
		Condition	**U**	T_MGB >= 0	4
		T_MGB < 0	(1)	T_MGB >= 0 && T_MGB < T_ED_max	3
		Else	1	T_MGB >= 0 && T_MGB >= T_ED_max	2

Running the model with NEDC cycle for 1200 seconds results the system response in the following graphs. Where the input is the requested torque and speed from the driving cycle and the output is:

A. *Equivalent fuel consumption:*

Figure 7 plots equivalent fuel consumption in response to requested torque over time. This plot shows a spike of consumption at the beginning of the cycle, due to the big inertial forces at takeoff, when the vehicle takes off and gains momentum, this consumption decreases significantly and is in the same range through out most of the cycle. Because the consumption will be used only for acceleration. At the end of the cycle after second 1000. There is another increase in fuel consumption to compensate the requested torque for the final acceleration.

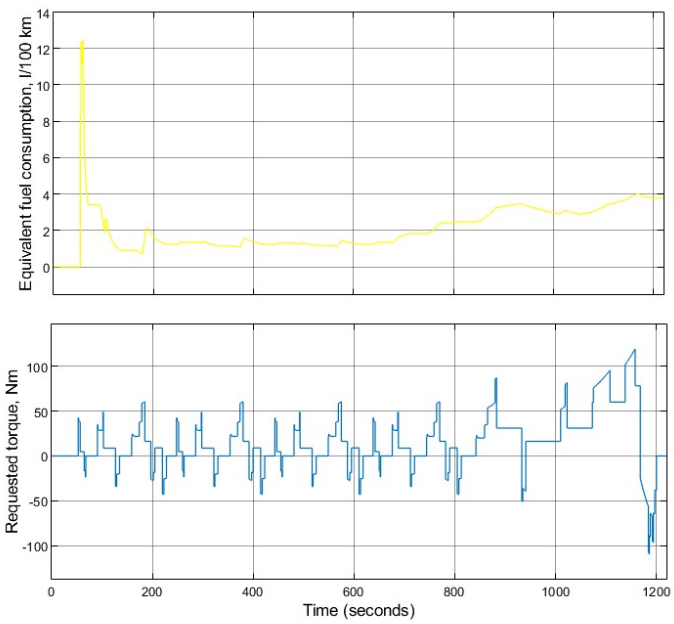

Figure 7 fuel consumption in response to requested torque

B. *State of charge:*

from the plot in figure 8, the SOC starts with an initial value, this is the value we try to keep at the end of the cycle.

At the beginning of the cycle, the speed is low so the ED driving mode is on, this will consume the battery charge and reduce the SOC, this reduction will continue until the charge reaches a critical threshold which is 15%, then charge mode will be activated and this explains the increase in the plot again, where SOC keeps going up until it reaches the upper threshold and charge will stop again at SOC=40%.

At the end of the driving cycle. A decrease of speed takes place. And comparing with the negative value of the requested torque from the previous figure, this indicates a braking case, which means pulse in SOC value due to regenerative braking, and this explains the increase in the SOC value at the end of the cycle, which leads back to the initial value of 50%. this means that the save in fuel consumption came with no penalty on battery charge and this is another significant result of this model.

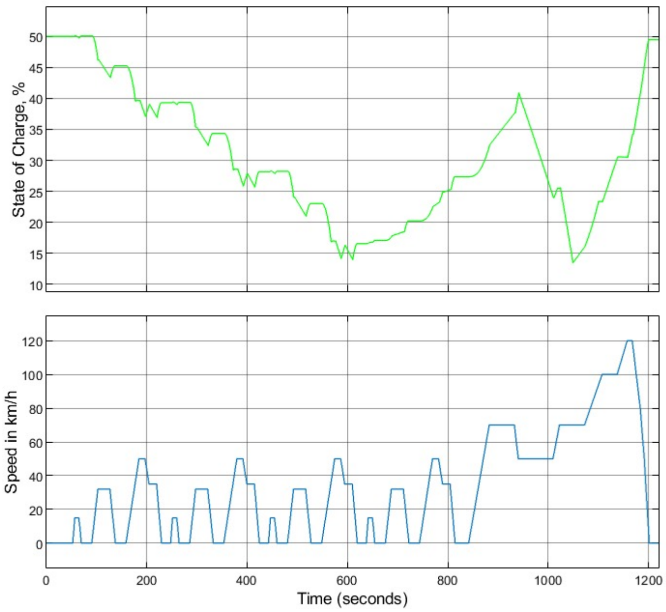

Figure 8 the SOC response to the requested torque

C. *Split ratio:*

The split ratio between the EM and the CE is referred to as U and is shown in figure 9, where the maximum split ratio is 1 which is ED mode, and the minimum value is -0.33 as stated in table 3 which represents a generation mode. A value of U=0 represents a pure CE mode.

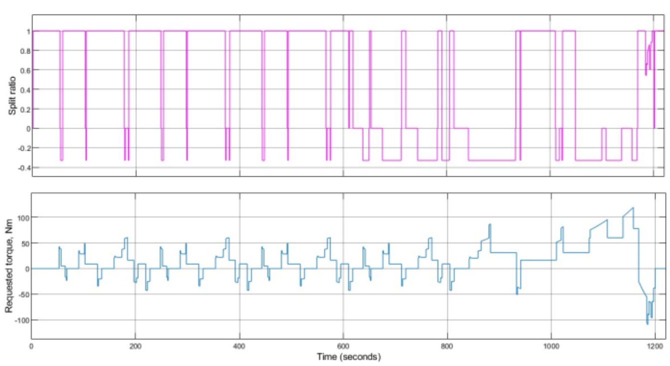

Figure 9 split ratio over NEDC drive cycle

D. *Fuel consumption*

The most important factor in this test is the fuel consumption. In the following figure, a comparison between the fuel consumption of conventional and hybrid version of the same vehicle. The graph shows a decrease from 4.5 down to 3.7 l/100km which is 19% for NEDC cycle. In addition to the const SOC level at the beginning and end of the cycle as shown in fig 10. This achieves the objective of this research.

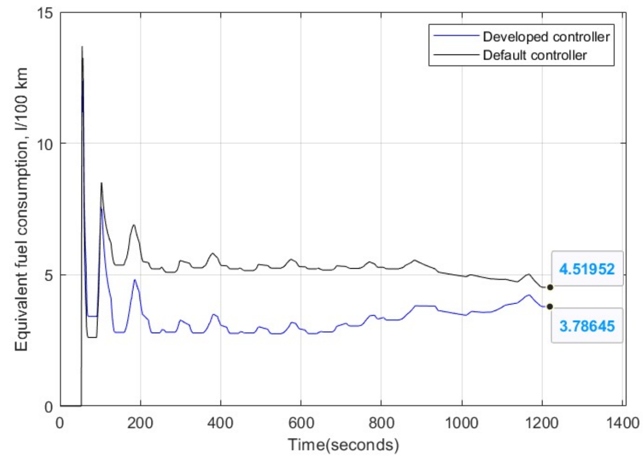

Figure 10 fuel save between the model with and without a controller

IV. CONCLUSION AND FUTURE WORK

A. *Conclusion*

In this paper we have observed developed Deterministic Ruled-Based energy management system. This system, as a representative of the energy management systems with relatively low complexity, showed us nevertheless significant decrease in the fuel consumption regarding conventional vehicle: 19.3% and 26.4% for NEDC and FTP-75 respectively. However, it's worth noting, that according to the Fig.8 SOC is achieved only in the presence of the continual high requested torque during a given driving cycle. Therefore, these data must be interpreted with caution as a real driving cycle may substantially vary. Another crucial and contradictive point in this research is an implementation of the wide SOC window. Due to the main aim in the reduction of the fuel consumption the minimal SOC state is set to 14%, what is noticeably lower than 25-30% at which most of the lithium-ion batteries have perceptible voltage drop. This improper exploitation of the battery leads to the excessive wear. Thus, even implementation of the basic energy management strategies demands in practice accounting all possible constraint factors considering not only overall efficiency, but also initial, repairing and maintaining costs.

B. *Future work*

Due to the globally growing trends in the use of EV and PHEV in the world this area offers promising opportunities for researches and system design engineers. The accomplished research is of personal scientific significance because it will serve as a solid foundation for future successive research in this field. Results and experience received during preparation are stating, that for development of the almost unimprovable energy management systems broad competence in the Control theory and HEV structure and its components is required. It incites to scrutinize other energy management strategies and their efficiency on the utilized model. Furthermore, new advanced technologies in energy storage are getting more and more appealing for market and industrial application on a daily basis. And as the goal of energy management control systems is to effectively spread the vehicle's energy, accordingly the given model can be extended to make use not only of the lithium-ion battery, but also to operate in combination with super-capacitors, hydrogen fuel cells, flywheel energy storage and etc.

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