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Investigation of hybrid electric vehicle control systems

***Ibrahim Karatas*[a], *Recep Halicioglu*[b] and *Yusuf Fedai*[c*]**

[a]*Osmaniye Korkut Ata University, Department of Civil Engineering, Osmaniye, Turkey*
[b]*Osmaniye Korkut Ata University, Department of Mechanical Engineering, Osmaniye, Turkey*
[c]*Osmaniye Korkut Ata University, Department of Manufacturing Engineering, Osmaniye, Turkey*

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ABSTRACT

Although hybrid vehicles are not widely used, they have an important role in terms of energy saving in the world. Control systems are one of the most important mechanisms in these vehicles for efficiency of energy usage. In this study, it is explained what the control systems of hybrid electric vehicles (HEV) are used and how they are used by review them. It is firstly shown how the internal components of the hybrid vehicle are controlled by the control systems and how the control unit is placed. The control systems are then individually classified among themselves. Control systems that are divided into two groups, which are rule based and optimization based, are collected under these two main headings.

1. Introduction

Nowadays, there are activities in our country about efficiency and saving because of bad environmental conditions, oil dependency and limited energy. Particularly vehicles are one of the most important factors in terms of efficiency and saving of fuel, emission that are environmental effect. One of the solutions for zero emissions is to produce vehicles that use only electrical energy. However, electric vehicles have not been superior to internal combustion motor vehicles in terms of energy capacity. For these reasons, hybrid vehicles have been developed using both electric power and internal combustion engines have started to be used. Hybrid vehicles use an electric motor instead of an internal combustion engine due to the low efficiency of braking in city traffic and in the case of stop-and-go situations. In interurban roads, internal combustion engines are used. Hybrid vehicles may have advantages in terms of fuel consumption and emissions other than internal combustion vehicles, some of which may be smaller than the engine, and may be recovered from freely generated energy. This makes it complicated in hybrid vehicles and it is necessary to control these components which move the vehicle. In order to the well control systems, an appropriate mathematical model has to be created.

In Figure 1, It is shown how to assemble engines, generators, batteries and the power control unit that controls them on the interior of the vehicle in the new generation hybrid systems, which is taken from Toyota's Global Strategy Report data [1].

The working scenario of a hybrid vehicle with control systems is as follows [2]:

- *Start and low speed;* the internal combustion engine does not start. Automobile is only actuated by the electric motor in operation.
- *At normal driving speed;* the internal combustion engine is divided in two sections by the power transmission unit. First part of the power is firstly transferred to the generators for the operation of the engine, and the remaining power for the internal combustion engine is transferred directly to the wheels. This operating principle is checked for maximum efficiency.
- *Acceleration;* In this case, power is provided from the internal combustion engine and electric motor as well as from the battery because of the extra power required.

* Corresponding author. Tel.: *+90-328-8271000*; Fax: *+90-0328-8250097*
E-mail address: *yusuffedai@osmaniye.edu.tr*
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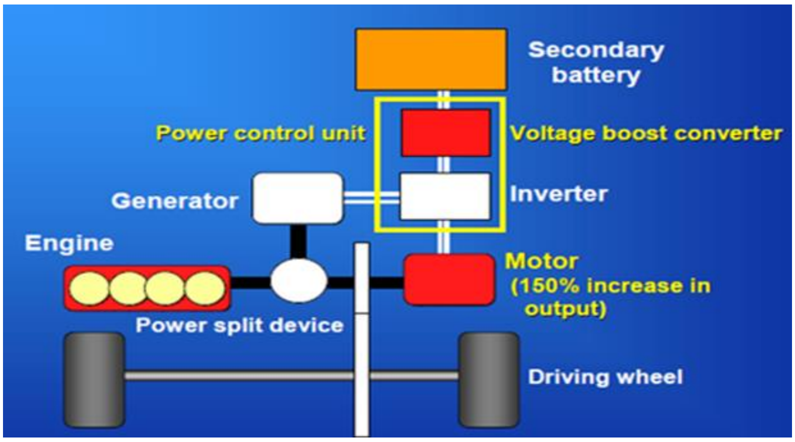

Figure 1. Schematic representation of internal components in the hybrid electric vehicle (block diagram of Toyota Next Generation Hybrid System) [1]

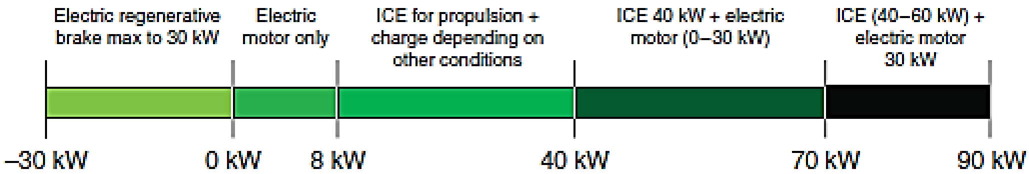

Figure 2. Working principle of hybrid electric vehicle [11]

- *During deceleration and braking*; the kinetic energy obtained when the braking is converted to electric energy for charging the battery.
- *The charge of the battery* is checked for min and max levels. When the battery is approaching the end of charge, the internal combustion engine will drive the generator and allow it to charge.

Figure 2 shows how the hybrid electric vehicle must operate via the control system for an example. If the vehicle demand power is less than 8 kW, only the electric motor is used to drive the vehicle. If the demand power of the vehicle is between 8 and 40 kW, the internal combustion engine empowers the vehicle and depends on the state of charge the battery is charging. If the vehicle demand is between 40 and 70 kW, the internal combustion engine generates a constant 40 kW of power and the electric motor generates additional mechanical power to meet the power requirement. If the vehicle demand is between 70 and 90 kW, the electric motor will draw a maximum of 30 kW and the internal combustion engine generates additional power to meet the power requirement of the vehicle [3, 11].

Figure 3 shows the interconnections and interactions of the internal components in the hybrid vehicle with each other in the control system. Where the electric motor produced by the generator is more than it consumes, the excess electrical power is loaded into the battery. Or if the generator produces less than the electric motor consumed, the battery is charged with electricity and transferred to the motor. The electric power distribution control meets the specified requirements of the signals, the internal combustion engine, the generator and the electric motor according to the given command values. The internal combustion engine controller, the generator controller and the electric motor controller control the internal combustion engine, the generator and the electric motor, respectively, in order to obtain the command values of the electric power distribution control [4].

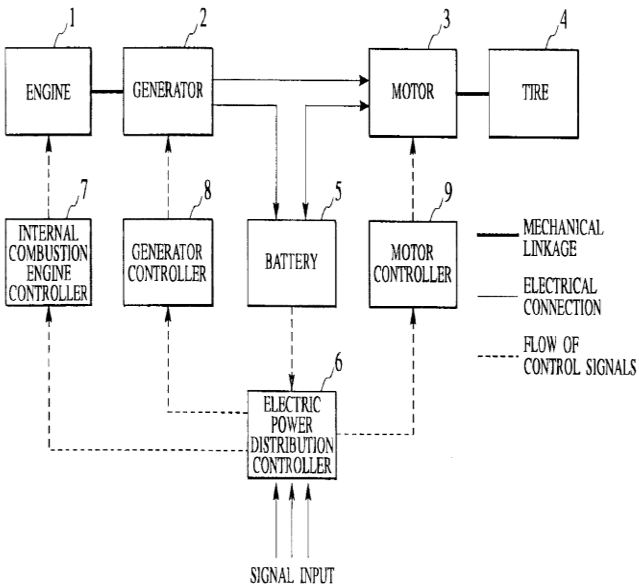

Figure 3. Block diagram showing control system of hybrid vehicles [4]

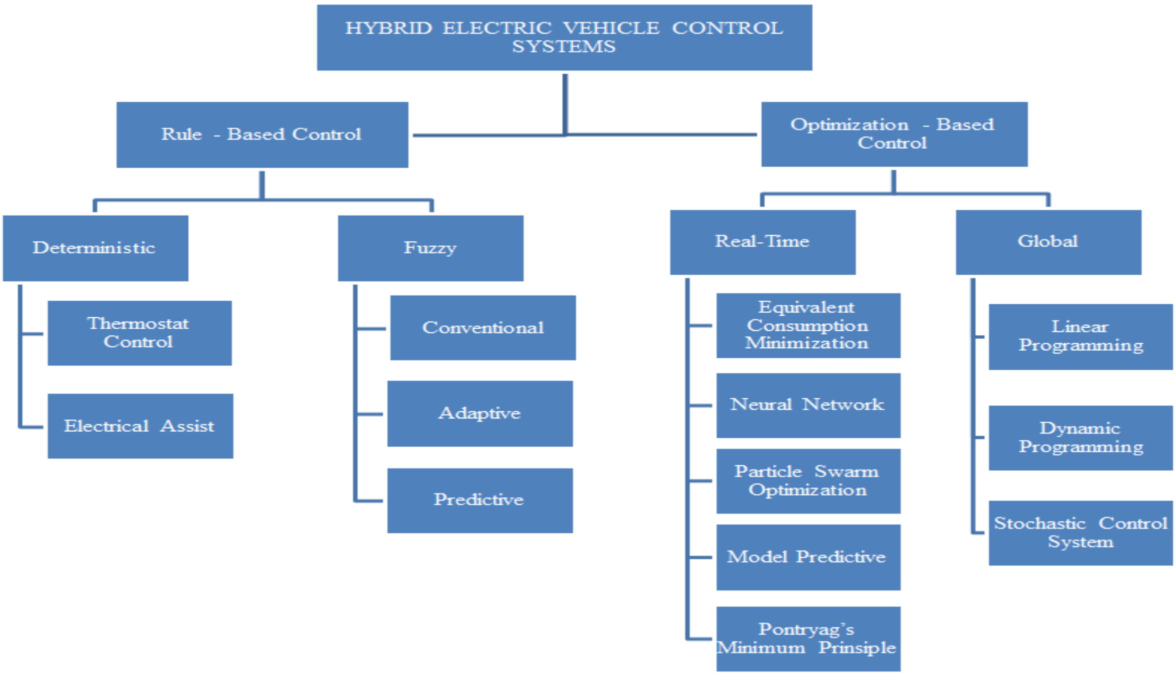

Figure 4. Classification of control systems of hybrid electric vehicles

2. Hybrid Electric vehicle Control Systems

The control systems of hybrid electric vehicles can be classified as shown in Figure 4 [5].

2.1. Rule-Based Control System

This system enables the components in the hybrid vehicle to work most efficiently using rule tables or flow charts. Decisions are made only with instant inputs. The rules used in this control system are as follows [3].

1. Only electric motor is used at low power and speed.
2. Both electric motor and internal combustion engine are used at high power and high speed.
3. In long roads, ie in stable driving conditions, only internal combustion engine is used.
4. An internal combustion engine is used to charge the battery and provide power to the electric motor depending on the charge state in the battery.
5. Maximum regenerative brake is used.
6. The efficiency of the hybrid system is optimized by controlling the power of the electric motor.
   - An electric motor is used to drive the internal combustion engine to higher efficiency zones.
   - If the speed of the electric motor is optimum, the battery is charged.
   - The charge state of the battery is kept at 0.5-0.7 for efficiency and higher battery life.
   - The battery is charged when the demand for the vehicle is low.

The rule-based control system is divided into two subcategories.

2.1.1 Deterministic Rule-Based Control System

Fuel economy and emission data, internal combustion engine operating maps, power flow in powertrain, and people's driving experience can help in the design of deterministic rules [6].

M. Zaher and S. Cetinkunt [7] developed a rule-based control system for reliable control and divided the subcategories of the deterministic control system into a working cycle.

Thermostat control system: In this system, two charging states are determined by looking at the efficiency map of the battery which will be opened and closed according to the motor charging state. These two values are designed to cover the most efficient region in the operation of the battery. According to this system, if the battery reaches low level, the internal combustion engine starts to work and the battery continues until it is charged. Then the internal combustion engine stops and remains the same until the battery is discharged. This cycle repeats itself [8].

Electrical assist control system: The internal combustion engine providing the power source and the operation of the electric motor provides the additional required power. Because the internal combustion engine performs charging, the battery charge status is preserved in all operating modes [10].

2.1.2 Fuzzy Rule-Based Control System

The fuzzy logic system is a form of reasoning developed from the fuzzy set theory. This system is used in decision making by coding in the rule base. One of the advantages of this system is that it can be adjusted at any time. This makes it easier to control the hybrid vehicle. Because it is nonlinear, it may be more suitable for complex structures such as powertrains [9].

Conventional fuzzy rule-based control system: This system uses optimum fuel usage and fuzzy efficiency modes to control the operation of the transmission organs. The fuzzy efficiency mode inputs as input the charge state of the battery and the desired internal combustion engine torque. Accordingly, the operating point of the internal combustion engine is set. The power required by the electric motor is equal to the difference between the required total power and the incoming power from the internal combustion engine. The fuzzy-based control system diagram is shown in Figure 5 [3]. This system calculates the power that comes from the vehicle speed, demand power and charge state of the battery. The calculated power is sent to the fuzzy-based controller to calculate how much power the electric motor should produce and how much power the internal combustion engine must produce to meet the total power requirement. For example, the fuzzy logic calculated motor power is determined as 7 kW for an internal combustion engine to meet a power of 25 kW in a 18 kW regulated vehicle [11].

Adaptive fuzzy rule-based control system: This system can optimize both fuel efficiency and emissions at the same time. But emissions and economy are contradictory. Therefore, a completely optimal solution cannot be obtained. Weighted total approach optimization of conflicting goals is used to achieve an optimal solution. Relative weights are assigned to each parameter according to their importance in different driving environments. This control system can control any of the targets by changing the values of the weights. In addition, there is a decline in vehicle emissions, ignoring the fuel economy [10].

Predictive fuzzy rule-based control system: This system can be solved when there is heavy traffic or using the global positioning system (GPS). Due to its robustness and speed, it is recommended to use it for non-linear and indeterminate systems. In the case of Salmasi2, it is a wise decision to recharge the battery to use a motorized vehicle if you are on a highway with heavy traffic in the future. This means that non-optimal solutions of real-time algorithms can be shifted to near optimal solutions by predictive control. For this system, a fuzzy logic predictor controller was developed at Ohio State University. It adapts the speed estimates that occur due to the traffic situation in the future with the current controller parameters. The input of this system is the change in vehicle speeds, the speed condition of the vehicle in the front zone, and the points determined along the route in the navigation system. The output is a GPS signal that tells the main controller to charge or use the batteries according to future vehicle conditions. For example, if navigation gives downhill and faster traffic warnings, the estimated controller tells you not to use the battery [12].

2.2. Optimization-Based Control System

The objective in optimization-based control system is to minimize the cost. In a hybrid electric vehicle, the cost function depends on emissions, fuel consumption and engine torques. Optimization based control system is examined under two main headings as real time optimization and global optimization.

2.2.1 Global Optimization-Based Control System

For the global optimization system, the battery charge status, driving conditions and response are also required at the same time. This system is more difficult to implement than real-time optimization due to account complexity. Delprat et al. assume that the fuel consumption and emissions are reduced, a global optimization algorithm has been developed [13].

Linear programming: This system is an important system in terms of fuel economy optimization. Fuel economy optimization generally used in serial hybrid vehicles. This problem can be solved by linear programming of the global optimal-based control system. Tate et al. [14] proposed to solve the nonlinear optimization problem of the hybrid vehicle by linear programming method to find the fuel efficiency by controlling the gear ratio and torque in the transmission organs. Pisu et al. [15] have designed a balanced and robust controller that uses linear matrix inequalities for fuel consumption, that is, for the powertrain of hybrid electric vehicles to optimize the economy.

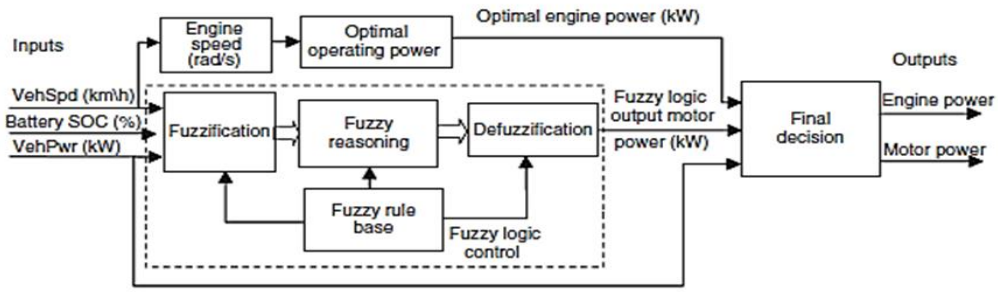

Figure 5. Fuzzy-based control system diagram [11]

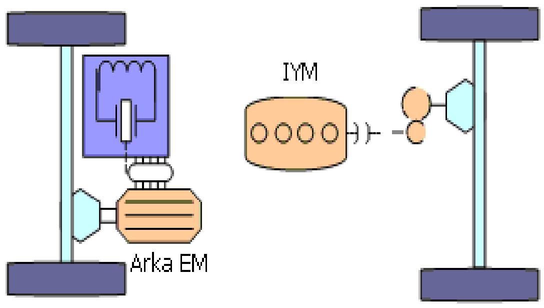

Figure 6. Vehicle model for dynamic programming [27]

Dynamic programming: This system was used by Richard Bellman16 in 1950, and the parts of the optimal system are also based on optimal. According to this principle, if the way between x(0) and x(p) is the optimal path, then the sub-ways between x(k) and x(k + 1) have to optimum (0<k<p). Dynamic programming is both a mathematical optimization method and a computer programming method. It can be used in linear or non-linear systems. At the same time, this method is preferred because it is difficult for analytical solution to have a large number of components in hybrid vehicles. For dynamic programming, the vehicle model shown in the figure 6.27 is used. The vehicle can be driven by an electric motor at the rear, while the front motor is driven by an internal combustion engine.

Stochastic control system: This control system is formulated as a stochastic dynamic optimization problem on the infinite horizon. The power demand from the drive is modeled as a random Markov operation. Markov operation predicts future power demands by producing probability distribution. The stochastic control system can solve ambiguous optimization problems using stochastic dynamic programming. This stochastic dynamic programming algorithm is found to be better than the deterministic control system [10].

2.2.2 Real Time Optimization-Based Control System

As mentioned in the previous section, global optimization does not control the cost function of the parameters to an instant optimization and changes in charge state. Real-time optimization is used to control the battery charge status [10].

Johnson et al. [18] have designed controllers that estimate energy consumption and emissions for each identified point. They used efficiency and emission optimization in a parallel hybrid electric vehicle with a real-time control system.

Equivalent consumption minimization: Paganelli et al. [19] addressed the concept of equivalent fuel consumption. Equivalent fuel consumption minimization does not require prior knowledge of driving and is implemented in real time. It provides a solution by calculating the amount of fuel equivalent as a function of online measurement. The total fuel consumption in the hybrid electric vehicle is the sum of the equivalent fuel consumption values taken from the internal combustion engine and the electric motor. Because of this, both the energy used in the battery and the fuel consumption of the internal combustion engine are given together. The equivalent fuel consumption minimization control system does not use future forecasts and can compensate for the uncertainties in dynamic programming.

Neural network control system: McCulloch and Pitts first designed a neural network in 1943 under this system. An artificial neural network is a parallel computation method which is composed of many connected processes. This method uses the principle of function approach. Neurons are used in the artificial neural network, and the weights of these neuron inputs and the deviation function give rise to the neuron output. The main purpose of this system is to calculate the output of all nerve cells. The adaptation of the neural network and its fit to the look-up table makes it better than the rule-based control system [20].

Arsie et al. [21] modeled a dynamic system with the components of the vehicle. According to this system, the vehicle load estimation is realized by optimizing the control system used for the optimum performance of the vehicle by using the neural network system.

Particle swarm optimization control system: This system was developed in 1995 by Eberhart and Kennedy [22]. This technique is used for continuous nonlinear processes and is inspired by birds in the nature. It is a recursive optimization using particles. These particles wander around a search field. All the herds are directed to the best position within this area and are repeated in this way. The operating system in this way can appropriately determine the energy flow direction and quantity in hybrid electric vehicles. Therefore, it works with high efficiency in powertrain and reduces fuel consumption.

Desai and Williamson [23] optimized drivelines and control systems using particle cluster optimization to reduce fuel consumption and emissions in their work.

Model predictive control system: This control system is a good method for dynamic models. The model prediction control system ensures that the current time is optimized using the future time. At the same time, the control system can take precautions by foreseeing future events [10].

West et al. [24] used this method to increase the life of the battery, thereby reducing the toxic emissions while increasing the range that the vehicle can go through. It starts oscillations in hybrid electric vehicles.

Pontryagin's minimum princible: This principle provides the necessary conditions for the optimization of the problem rather than the direct calculation of the control process [25].

In 1956, the Russian mathematician was formulated by Lev Semenovich. It is an example of the Euler-Lagrange equation. This system provides only the necessary conditions with the Hamilton-Jacobi-Bellman equation for optimization.

Stockar et al. [26] proposed a model-based control system to reduce emissions the most. This control system has been transformed from the global optimization to the local optimization with the minimum principle of Pontryagin to ensure optimal energy use for hybrid vehicles.

Table 1 compares the control systems used in hybrid electric vehicles to understand the advantages and disadvantages of the control methods [10]. *S. Comp, C. Time and S. Type* present structural complexity, computation time and type of solution, respectively. Requirement of prior knowledge is also given in this table.

3. Conclusion

In this study, the components of the hybrid vehicle, the internal combustion engine, the electric motor, the generator, the battery and control systems that optimize the performance of the hybrid electric vehicle in terms of fuel efficiency, emissions and cost are presented. The most appropriate power flow control schemes implemented by controllers in series, parallel and series-parallel systems are shown. In order to find the most suitable method among the control systems mentioned in this study. The lower structural complexity, the shorter calculation time and the global solution type are suggested. When we look at these situations, it is more appropriate to use the fuzzy method and model predictive control systems. However, it is still unclear which one is most appropriate, whether or not there is a need for preliminary information.

Table 1. Comparison of control systems used in hybrid electric vehicles

Control System	**S. Comp.**	**C. Time**	**S. Type**	**Prior knowledge**
Fuzzy logic	No	Small	Global	Yes
Particle swarm optimization	No	More	Global	No
Energy consumption minimization strategy	Yes	Small	Local	No
Pontryagin's Minimum principle	No	Small	Local	Yes
Dynamic Programming	Yes	More	Global	Yes
Model predictive	No	Small	Global	No
Stochastik control	Yes	More	Global	No
Neural network	Yes	Small	Global	Yes

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