A fuzzy controller for two energy storage management system in electric bicycle

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Abstract
This paper presents an energy management system for an electric bicycle that runs in local community in Thailand. Fuzzy logic technique is applied in this system to control supercapacitor and battery management according to the demand of load power. The load of the electric bicycle depends on speed of each driving cycle. Mamdani-based fuzzy logic controller is selected to control the ratio of output between supercapacitor and lead acid battery. Fuzzy logic controller aims to reduce battery usage during peak current occurred from the electric bicycle and passes speed bump in order to extend the lead acid battery life time.

Keywords: Fuzzy logic control, Energy management system, Speed bump, Electric bicycle.

1. Introduction
In the last few years, Plug-in Hybrid Electric Vehicle (PHEV) and Battery Electric Vehicle (BEV) in Thailand has become more popular due to its zero emission [1]. The number of registered cars accumulatively increase from 7705 to 156,038 cars during of 2015-2019 [2]. Electric bicycle is one type of EV that has become more popular to use in city area. It is used to replace motorcycle and bicycle for people who travel less than 20 km. People prefer to use electric bicycle because no driving license needed, ecofriendly, easy to maintenance and the price is cheaper than an internal combustion motorcycle. For the electric bicycle to become cheap and easy to maintenance lead acid battery is used as energy storage. Government launches many policies such as zero tax for Electric Vehicle (EV) manufactured in Thailand, 100,000 baht subsidy for users who buy EV [3], and support to industries and researches to create more EV.

One of the most important research topics is the development of energy management systems for battery. Energy management system is one of the most essential systems in EV because battery is the most important part to make EV running. The better energy management system could extend the driving range of the EV. Due to the limitation of the battery Hybrid Energy Storage System (HESS) as shown in Figure 1. This system is applied to the system to help increase driving range and extend battery lifetime [4].
The previous research of HESS is used to manage two energy sources i.e., fuel and battery. Since EV has been more popular the manufacturers and researchers want to change from fuel to battery and other types of storage system. The problem of pure EV is car acceleration required high power battery causes insufficient energy for the battery to distribute power to motor. On the other hand, only the battery is not enough for the EV. As the result of, the present studies try to develop a HESS which uses supercapacitor to improve insufficient energy [5]. Supercapacitor is a new type of energy storage that can distribute high power with a rapid charge and discharge rated [6]. HESS between supercapacitor and battery is importance to use logic control and design the power distribution at different situation [5]. There are many types of logic control for HESS. Simple frequency decoupling technique which separates power demand by using low pass and high pass filter. Supercapacitor is applied for transients and peak loads [7]. The load can be classified by low and high frequency. The control method for energy management system in solar panel –battery super capacitor hybrid energy system in solar car is utilized by if-clause algorithm [8]. Fuzzy is a Linguistic language that represents the human words or feeling into value that computer understands. Therefore, fuzzy is not commonly use with HESS. The research about Fuzzy usually uses with air-condition and electric water heater [9][10]. It is found that the fuzzy algorithm can be applied for energy management for EV. Thus, this research focuses on fuzzy logic in HESS in EV of supercapacitor and battery.

Electric bicycle is used in as a parameter to build fuzzy logic control. However, this logic control can be applied for EV in the future. The influence factors in fuzzy logic control are the following: First, the effect of the ratio between battery and supercapacitor. Then, the speed differentiation. This research is to study on experiment in MATLAB Simulink. Bangkok Driving Cycle and speed bump to evaluate the fuzzy logic control algorithm[11]. For extension of the lead acid battery lifetime.

![Hybrid Energy Storage Management System](image)

**Figure 1.** Hybrid Energy Storage Management System.

2. Nomenclature

| Symbol | Description |
|--------|-------------|
| A      | Frontal area of vehicle (m²) |
| α      | Gain |
| \( C_d \) | Drag coefficient |
| \( F \) | Force (N) |
| \( F_t \) | Tractive force (N) |
| \( g \) | Gravity force (N) |
| \( m \) | Mass (kg) |
| \( P \) | Electric power (W) |
| \( \rho_{\text{air}} \) | Air density (kg/m³) |
| \( R_a \) | Aerodynamic drag resistance (N) |
\[ R_i \quad \text{Inertial resistance (N)} \]
\[ R_g \quad \text{Grade resistance (N)} \]
\[ R_r \quad \text{Rolling resistance (N)} \]
\[ \mu \quad \text{Rolling resistance coefficient} \]
\[ v \quad \text{Speed vehicles (m/s)} \]

3. Methodology

3.1 Hybrid Energy Storage System (HESS)
HESS in this system uses fuzzy logic control to evaluate the amount of the power load from the electric bike. Battery and Supercapacitor are input for fuzzy that can distribute energy depend on load. Power load is input for fuzzy but demand energy.

\[ P = F \cdot v \quad (1) \]

The electric power can be obtained from by total resistance force and vehicle speed as illustrated in Equation (2)

\[ P = (R_a + R_r + R_g + R_i) \cdot v \quad (2) \]

3.2 Energy consumption [12]
The total energy consumption can be derived by total force and vehicle speed as shown in Equation (1)

\[ F = R_a + R_r + R_g + R_i \quad (3) \]
The total force act on bicycle is shown in Figure (3).

\[ R_a = \frac{1}{2} C_d \cdot \rho_{\text{air}} \cdot A \cdot v^2 \] (4)

Aerodynamic drag resistance is the air resistance during the vehicle moving which is calculated by the Equation (4). The 1.1 of drag coefficient \( C_d \) is applied with 1.1839 kg/m\(^3\) of air density in this experiment.

\[ R_r = \mu \cdot m \cdot g \cdot \cos \theta \] (5)

Rolling resistance is the resistance occurring on the wheel turns on the surface which related to the weight of the vehicle as shown in Equation (5). The 0.04 of rolling resistance coefficient tire turns on asphalt road, 90 kg of mass for electric bike and driver [8]

\[ R_g = m \cdot g \cdot \sin \theta \] (6)

Grade resistance is the resistance that occurs when the vehicle travels up or down the slope. As shown in Equation (6). In this experiment the vehicle runs on plain path which have less gradient even the speed reduces. The road grade (\( \theta \)) is almost zero degree thus the grade resistance is neglected.

Figure 3. Forces acting on bicycle.
3.3 Fuzzy logic control

The first step of Fuzzy Logic Control (FLC) is to transform linguistic language into computer language as an input for FLC and make a decision with its own algorithm that the user designs to get the desirable output, for example in the Figure 4 the temperature control of the water. Normal control can only separate on and off the heater as 1 and 0. However FLC separates the input into more detail i.e., cold, cool, nominal, warm and hot. Then substitute all this feeling into the computer language.

![Traditional logic vs Fuzzy logic comparison](image)

**Figure 4.** Comparison of water temperature control[13].

For the algorithm of design part, the all-output responses from each input are needed to know for design of the control algorithm based on real data as shown in Figure 5. However, the unknown output result from FLC algorithm by using the function design fuzzy in MATLAB then importing the fuzzy file into the control algorithm.

![Fuzzy logic control design in MATLAB](image)

**Figure 5** Fuzzy logic control design in MATLAB.

3.4 Bangkok driving cycle

Bangkok driving cycle is the standard for test of the vehicle fuel consumption and power consumption in Thailand. Bangkok driving cycle consists of 6 phases as shown in Figure 6 and 7. As the previous research, this driving cycle was applied for study of motorcycle. Thus, the Bangkok driving cycle is expected to apply for the experiment of electric bicycle. Following the Bangkok driving cycle the speed is calibrated by gain of 0.3 to comply with electric bicycle. The speed is used to calculate the power consumption of electric bicycle for this driving cycle based on the theory of bicycle model.
The relation of speed according to the Bangkok driving cycle is shown in Figure 8. In case of driving cycle is applied without supercapacitor, the battery has to supply all the power for the load.
Table 1. The simulation parameters for electric bicycle.

| Parameter                          | Value          | Unit   |
|------------------------------------|----------------|--------|
| Cross Section Area \( (\alpha) \) | 0.8×0.5×1.6    | \( m^2 \) |
| Air Density \( (\rho) \)           | 1.1839 at 25°C |        |
| Drag Coefficient \( (C_d) \)       | 1.1            |        |
| Mass \( (m) \)                     | 90             | kg     |
| Gravity Force \( (g) \)            | 9.81           | \( m^2/s \) |
| Rolling Friction Force \( (R_f) \) | 0.018 at dry asphalt |        |
| Slope \( (\Delta) \)               | 0              | degree |
| Angle                              | \( \Delta = \frac{180 \cdot \pi}{rad} \) |        |

3.5 Specification of electric bicycle

Table 2. Specification of electric bicycle.

| Specifications                  | DC Gear Motor SNK 24 V 250 W |
|---------------------------------|------------------------------|
| Motor                           |                              |
| Battery                         | Battery 6 lead acid Yuasa YTZ5s 2 series then 3 parallel 24 V |
| Supercapacitor                  | 350 F, Nominal voltage 2.7 V, 6 series |

Speed bump characteristic is collected by the experiment with variable parameter in this study. The illustration of actual experiment is represented in Figure 9.
Figure 9. Actual experiment of speed bump.

3.6 Fuzzy algorithm

The fuzzy algorithm is designed based on real experiment. The maximum power load, steady load battery and supercapacitor characteristic are used to design the fuzzy input and output as shown in Figure 10(a) and Figure 10(b). There are two rules in this fuzzy algorithm. In the first condition, if the power load is steady with the power between 50 to 200 w then the battery is on. In the second, when the power load is 125 w to 300 w then battery and supercapacitor is turned on. As show in Figure 10(c). The ratio of turned on and turned off supercapacitor and battery for switch control is represented in Figure 11.

Figure 10 (a) Power ratio of supercapacitor.

Figure 10 (b) Power ratio of battery.
Figure 10 (c) Relation between power and power load ratio for steady and high loads.

Figure 11(a) Relations between battery ratio and turn-on switch.

Figure 11(b) Relations between supercapacitor ratio and turn-on switch.
4. Result

4.1 Bangkok driving cycle analysis
Bangkok driving cycle with FLC is shown in Figure 12. Supercapacitor is used to decrease the power discharge from the battery and provide the energy for meeting the power requirement. FLC is used to decide if the power require is more than 150 w. Then, FLC will sent signal to switch that control the output discharge of the supercapacitor as present in Figure 8. The status of the on and off switch that controls with FLC is shown in Figure 13.

![Figure 12. FLC power consumption analyzed on Bangkok driving cycle.](image12)

![Figure 13. FLC contact switch on Bangkok driving cycle.](image13)

4.2 Speed bump
In Thailand, there is a speed bump which is not concerned to the Bangkok driving cycle. Speed bump is usually found in the city area. The results show that at speed of 17.5 km/hr is observed at distance 10 m of brake distance. The average power for this speed bump is shown in Figure 14. This power is put into the simulation to test the power consumption of HESS.
Figure 14. Power consumption on speed bump for speed of 15, 17.5 and 20 km/hr.

The result of power consumption using FLC with the is shown in Figure 15 and the on off switch which controls with FLC the status of the switch is shown in Figure 16

Figure 15. Power consumption of power required, battery and supercapacitor on speed bumps.
5. Conclusion
Supercapacitors could be applied to reduce the power consumption of the battery. The HESS is used to manage the energy between the battery and supercapacitor. The energy management could be controlled automatically with FLC. Speed bump show high amount of impact in power consumption than the Bangkok driving cycle because of its characteristic of speed bump force the driver to break and accelerate again. The power consumption is increased by the speed bump.

The usage of supercapacitor can extend the lead acid battery lifetime because the peak load is distributing with the supercapacitor with its advantage of fast charge, discharge and long-life cycle time. So, it is suitable to use supercapacitor to help the lead acid battery. From the result speed bump is one of the most interesting parameters in EV HESS. So, in future work, the author will study effect of speed bump and other type of speed reducers in Thailand.

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