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Fuzzy Based Energy Management Algorithm for Hybrid Train Systems

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ABSTRACT

Energy management is one of the key issues in designing different types of hybrid vehicles, including cars, buses and trains. In this paper a hybrid train is studied in three modes of operation, using three different power sources. In order to keep the energy consumption at an optimum level, it is necessary to consider the characteristics of all the system's elements and also their optimum point of service.

A fuzzy logic based energy management system has been designed and implemented. The underlying subject of the fuzzy based energy management system is to optimize the efficiency of internal combustion engine, ICE, considering the other power sources as flywheel and battery. Simulation results have been used to evaluate the performance of the fuzzy logic energy management system.

Keywords: *Flywheel Energy Storage (FES), Hybrid Train Systems (HTS), Energy Management System (EMS), State of Charge (SOC)*

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Introduction

Increasing concerns on oil prices, pollution, global warming and future limitations on fossil fuels, have forced the railway industries to work more seriously on the development of hybrid electric and fuel cell locomotives.

Hybrid propulsion systems, using a combination of efficient energy storage and supply systems, not only provide an ICE system with optimal energy consumption but also can maintain the capability of energy recovery in braking mode (regenerative braking). [1], [2]

It is possible to use hybrid systems in two different design configurations as series and parallel hybrid configurations. Considering the advantages and shortcoming of each configuration for different applications, in this study a series hybrid system is modeled and analyzed.

Flywheel Energy Storage, FES, Systems

Flywheel Energy Storage systems, FESs, are considered as mechanical batteries. They propose some advantageous specifications upon ordinary battery systems, especially for hybrid electric trains. Their high specific energy and power, high energy efficiency, long life cycle and lower maintenance requirements are the main attractive features of FESs.

Comparing to electrical energy storage equipments, FESs are basically similar to ultra capacitors, with this difference that in FESs the energy is stored as kinetic rather than potential energy. There is a direct analogy between angular speed of a flywheel and voltage in an ultra capacitor. [3]

Energy storage flywheels are also useful in power conditioning applications, when there is a mismatch between the power generated and the power demand of the consumer.

In general FES based hybrid systems for railway trains can be designed in three different configurations as:

- Directly coupling the flywheel to the vehicle drive, via a Continuously Variable Transmission (CVT).
- Using a standalone flywheel assembly, in the train in the same manner as an electrical battery.
- Using the FES system as a stationary energy storage system installed in the stations, storing the regenerated energy during the braking mode of the train, in its approach to the station, and offering it to the train in its acceleration mode, when the train leaves the station.

Utilization of flywheels in HTS helps in supplying the high energy demand of the train, when it is in acceleration mode. This provides the basis for reducing the high level of fuel consumption, as is the case in diesel and/or diesel electric trains.

The FESs also supply part of the required energy for the train movement cycle, from one station to the next. This can help to reduce the ICE's operation duration. This will also provide the opportunity to operate the ICEs in their optimal efficiency condition.

HTS Configuration and Operation

Figure 1 represents the block diagram of HTS propulsion system including its power sources. In this design, the flywheel is considered as the main source of energy and it is charged in each station, to its maximum level of energy, about 2 MJ. The flywheels usually supply the train in acceleration mode, where the energy demand is in its maximum level.

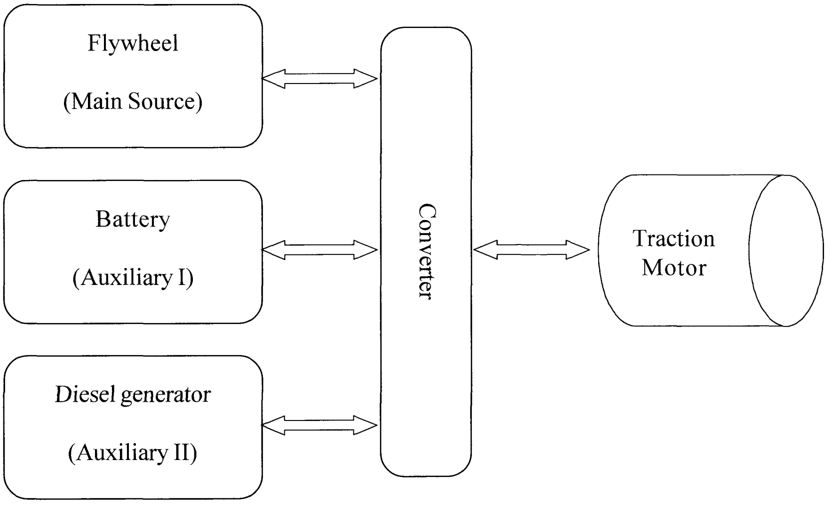

Figure 1: Block Diagram of the Hybrid Train System

The batteries as the first auxiliary source of energy have the role of supplying energy to the traction system, after the acceleration phase. The batteries usually provide the required energy in low demand mode of train movement, i.e. in constant speed mode. They have also the role of stabilizing the train power irregularities, due to the changes in demand, in regenerated and/or consumed energy.

The diesel-generator is considered as the second auxiliary source. The diesel-generator comes to service, when it is required by the Energy Management System, EMS, i.e. when the flywheel and batteries both have gone below a predefined State of Charge, SOC, levels. The SOC limit of the batteries, for this purpose, can be defined in a dynamic manner, considering the current and future energy requirements of the system.

In the studied system three different sets of variables as route profile, speed profile and driver commands are considered as inputs.

The EMS output depends not only on the individual energy sources conditions, but also on the forthcoming train speed and route profiles.

The energy management module of the system will determine a primary energy profile, based on the planned movement profiles and also efficiency and emission diagrams (maps) of the sources, stored in the system. The energy profile can be regulated later, in a dynamic way, in any unpredicted situations which might occur. These include the operational constraints, midway stops and/or speed alterations and so on.

Figure 2 shows the block diagram of the whole energy management and control system. The system is modeled and simulated in Matlab/Simulink environment. The results have been compared with the actual data provided by references [4] and [5].

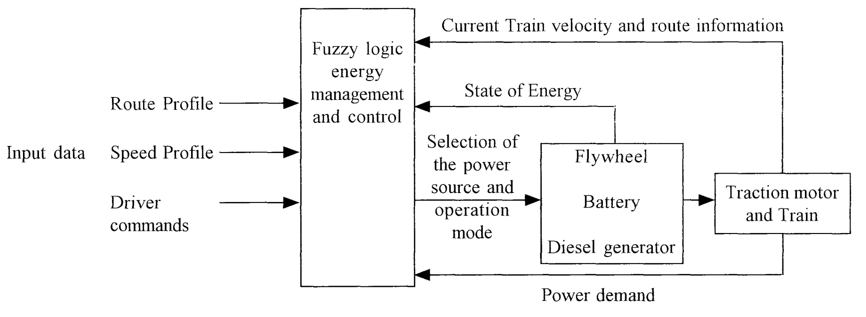

Figure 2: Basic Block Diagram of Power Controller

The following specifications have been considered for the system components throughout this research work:

- Permanent magnet motor: 80kW continuous,100 kW peak;
- Battery: 30 KW, 2 KWh;
- Total vehicle mass: 12000 kg.
- Internal combustion Engine: 63 KW

Table 1 provides the system, route and operation characteristics which are considered in determining the energy consumption. The information provided is based on a typical route, with a predefined speed profile. The train acceleration and deceleration are considered as 0.73 m/s^2 and 0.6 m/s^2 respectively.

Table 1: Vehicle, Route and Operation Character Performance Characteristics

	Values	Parameters
1	Max. train speed	45 km/h
2	Train acceleration	0.73
3	Number of axle	4
4	Max. line gradient	4%
5	Acceleration mode	17 s
6	Constant velocity	30 s
7	Regeneration mode	20 s
8	Total travelled	850 m

Energy Management System

The energy management system checks the state of energy of different sources and allocates them to the traction system, considering the predicted energy consumption profile.

If the total stored energy falls below a minimum predefined level, the diesel system will be turned on, although a reduction of train speed, in order to reduce the power demand of the system, has a higher priority than activating the diesel system. So the energy should be managed in such a way that:

1. Flywheel provides the required energy, as far as it is reasonable. The reasonability is determined by considering all mentioned and related data, including the future path of the train.
2. The batteries will provide the required energy in the low power demand mode.
3. ICE comes to service, considering the efficiency map and power demand
4. When traction motor goes to regeneration mode, the energy should be stored in the flywheel and/or batteries, based on their SOC levels.

Figures 3 and 4 represent the efficiency maps of permanent magnet motors/generator and ICE respectively. Figure 5 shows the power losses vs. the SOC of the batteries considered for this study. The maps are generated, using the Advisor modeling system introduced in reference [6].

Based on the efficiency maps of the energy sources and also the environmental and operational conditions, the EMS determines the optimal working points of flywheel, diesel generator and batteries.

An efficiency of 80% is considered for the flywheel, which corresponds to an SOC of 0.3 to 0.9. As Figure 3 shows, the maximum efficiency for generator is 90% for the speed range of 2000 to 3200 rpm.

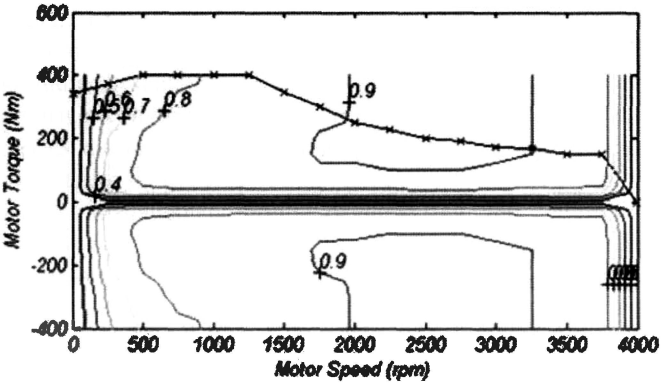

Figure 3: Efficiency Map of Motor/Generator

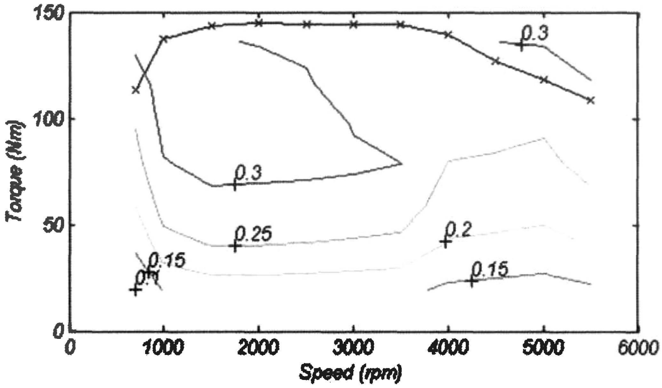

Figure 4: Efficiency Map of ICE

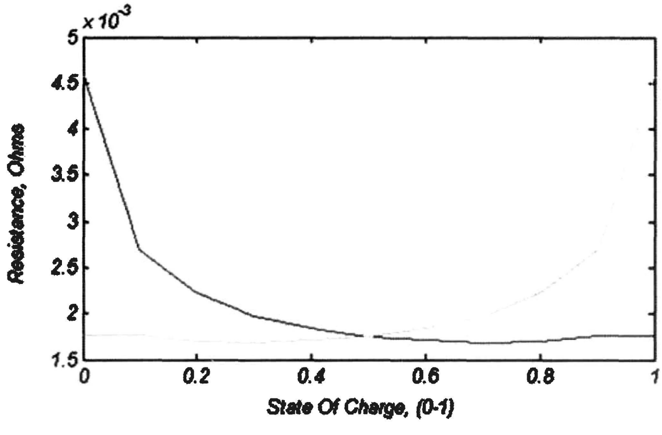

Figure 5: Resistant vs. SOC of Battery

In this range, a torque of 80 to 140 Nm can be provided, while for the ICE, a maximum efficiency of about 30% for a speed range of 1000 to 3200 rpm and a torque of 75 to 120 Nm is expected. Figure 4

So the optimum working points for a diesel generator should be determined based on both generator and diesel efficiency maps.

For batteries, as Figure 5 represents, the minimum loss is maintained between an SOC of 0.3 to 0.8, meaning that the EMS should manage to utilize the batteries and also keep them charged in this range.

Power Prediction and Computing

A reasonable energy management decision, for distributing the power load on the sources, should be based on a fair estimation of the current power requirements and also prediction of its forthcoming values. This requires information of the route profile, train load, operational requirements, stop point of train and etc. Having this information provided, the required energy can be determined by train resistance formula.

$$R_t = K_1 + K_2.V + K_3.V^2 + W.G/100$$

In above resistance formula, also known as Davis formula, the followings are considered:

- K_1, friction dependent resistance, a function of axle load, surface condition, rail and wheel profiles and bearings.
- K_2, coefficient of speed dependent losses, originated from flange friction, bumps, etc.
- K_3, coefficient of resistances dependent on square of speed. This includes air resistance which depends upon cross section area, shape, length, etc. of vehicle.
- $W.G/100$, Gradient resistance term, speed independent originated from up and downstream gradients. Gradient resistance is considered as the component of train weight which is parallel to the grade line.

Other resistances such as curve resistance are ignored in the above formula. Curve resistance is originated from friction of rail flanges against rails as the train moves on a curve. For a particular train, the Davis equation can be written as follows:

$$K_3 = (1.3\, w.n + 29\, n) + b.w.n.\,(at + v_0) + c.A.\,(at + v_0)^2 + 20\, w.n.G \tag{1}$$

$$E = \int_0^1 R_t.V.dt \tag{2}$$

$$E = \left(a\frac{t_1^{2}}{2}(1.3\,w.n + 29\,n)\right) + b.w.n.a\frac{t_1^{3}}{3} + c.A.a\frac{t_1^{4}}{4} + 20\,w.n.G.a\frac{t_1^{2}}{2} \tag{3}$$

Where:

R_t	=	resistance force (N)
n	=	number of axles
w	=	axle load (kg)
a	=	acceleration (m/s^2)
G	=	gradient (%)
A	=	area (m^2)
b	=	friction coefficient
c	=	drag coefficient

Fuzzy Logic Energy Management

After computing the power demand, the EMS is required to select the online power source and the rate of power generation at each particular duration and train movement phase.

The main idea behind fuzzy EMS is to model an expert operator capable of controlling the process without using a mathematical description of the process behavior as is the case in classical and modern control theories.

The fuzzy logic EMS is designed to take the responsibility of this task, because of the following reasons:

- The rule-based fuzzy algorithms are more flexible than the classic controllers.
- Fuzzy rule-based methods are inherently robust to system uncertainties [5] and [7].

Optimizing the efficiency of ICE is considered as one of the main aims in designing the fuzzy rules for the EMS. The fuzzy EMS operates the ICE in its optimal operating points (i.e. optimal torque and speed) defined by its efficiency map.

Inputs to fuzzy logic EMS are the batteries' SOC and driver movement commands. In the first step (fuzzification), membership degrees of the two inputs are computed using the membership functions (MFs).

Due to the fact that crisp signals are expected from the EMS, Sugeno-Takagi fuzzy controller is used in this system. The fuzzy rules specified for the system should cover the whole operation area of each particular power supply and traction motors.

Table 2 represents the maximum required power and energy for a typical light train for a route of 850 meters, specification of which is provided in Table 1.

Table 2: Energy and Power Requirement Data

	Parameters	Values
1	Max. power in constant velocity of 50 km/h	15 kw
2	Max. power in 0.7 m/s^2 acceleration	70 kw
3	Energy required for acceleration mode	1.76 MJ

The fuzzy rules planned for the EMS can be listed as follows:

- If E flywheel is mot low and P is high then generator mode is OFF.
- If E flywheel is low and P is low and SOC battery is not high then generator mode is ON and ? generator is 240 rad/s and T generator is 100 Nm.
- If E flywheel is low and P is high then generator mode is ON and ω generator is 550 rad/s and T generator is 100 Nm.
- If E flywheel is low and P is normal then generator mode is ON and ω generator is 240 rad/s and T generator is 100 Nm.
- If E flywheel is low and P is negative low or negative high and SOC battery is not high then generator mode is OFF.
- If E flywheel is normal and P is low then generator mode is OFF.
- If E flywheel is high and P is not high then generator mode is OFF.

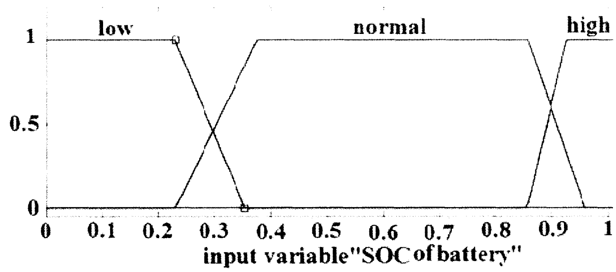

Figure 6: Membership Functions for SOC of Battery

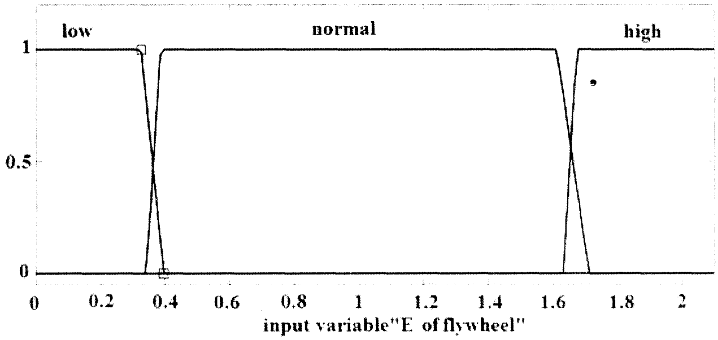

Figure 7: Membership Functions for Flywheel Energy

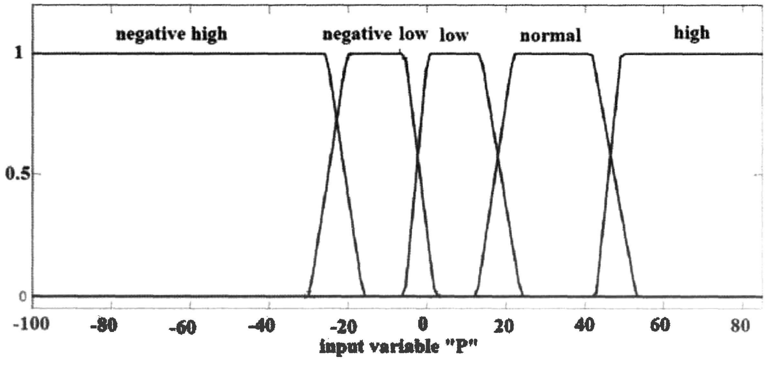

Figure 8: Membership Functions for Power Demand

Simulation Result

The EMS has been implemented and simulated with Matlab fuzzy logic toolbox. Figures 9-12 show the operating points of the ICE, generator and batteries. Figure 9 shows that the generator has been operated close to its optimal points, which is defined for it.

The operating points for ICE in figure10 shows that the ICE is operating close to its optimal points, in the speed range of *1600-3000* rpm and torque range of *75 -120* Nm.

The batteries are also operated in high SOC range from about 0.6 to 0.85, in which low power loss and high efficiency is expected.

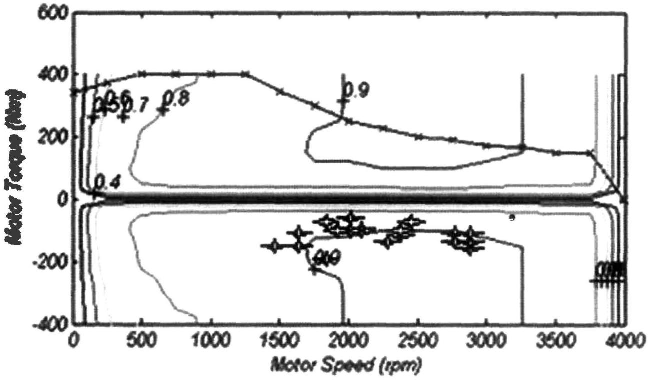

Figure 9: Operation Points of Generator, Using Fuzzy Logic EMS

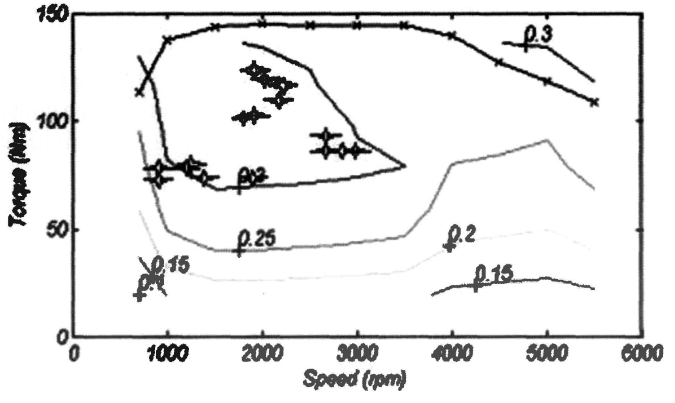

Figure 10: Operation Points of ICE Using Fuzzy Logic EMS

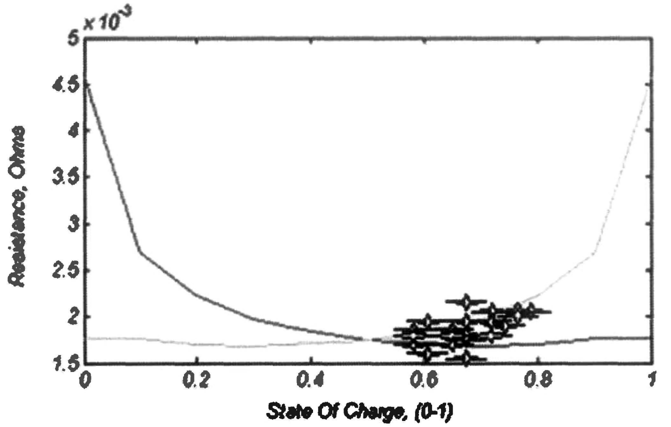

Figure 11: Operation Points of Batteries, Using Fuzzy Logic EMS

Comparing the results of this simulation, with what has been represented in reference [4], where a simple controller with similar parameters and conditions has been used; about 10% reduction in fuel consumption is achieved.

Conclusion

In this paper, a fuzzy logic algorithm for energy management of HTS systems is modeled and its performance is analyzed.

Utilizing a flywheel energy storage system, besides the batteries and a small size diesel generator provides different alternatives for the system, in terms of energy sources. The EMS optimizes the energy flow between the power sources in different modes of train journey, from one station to the other. The results show a considerable reduction in fuel consumption, by operating the ICE in its optimal working point.

Due to the fixed railway routes, the whole journey path can be considered in predicting the train's energy profile. This can be a useful area for future research.

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