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Renewable Hydrogen Hybrid Electric Vehicles and Optimal Energy Recovery Systems

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Abstract—**This paper investigates the design of an optimal energy recovery system for a hydrogen hybrid electric vehicle to allow increased range. The proposed system includes two different energy recovery sub-systems. These are; a regenerative braking sub-system and an active suspension sub-system. A dynamic model of this optimal energy recovery sub-system is implemented in MATLAB/Simulink™ and integrated with a hydrogen hybrid electric vehicle model to investigate the effect of the optimal energy recovery mechanism. The simulation results indicate the energy recovery and hence, lead to the extended range capabilities.**

Keywords – Hydrogen hybrid vehicles, Regenerative braking, Active suspension system, Energy recovery

I. INTRODUCTION

The increasing global demand of fuels together with and green house gas (GHG) environmental concerns, have progressively leads to the global trend towards low-emission and fuel efficient vehicles in recent years [1].

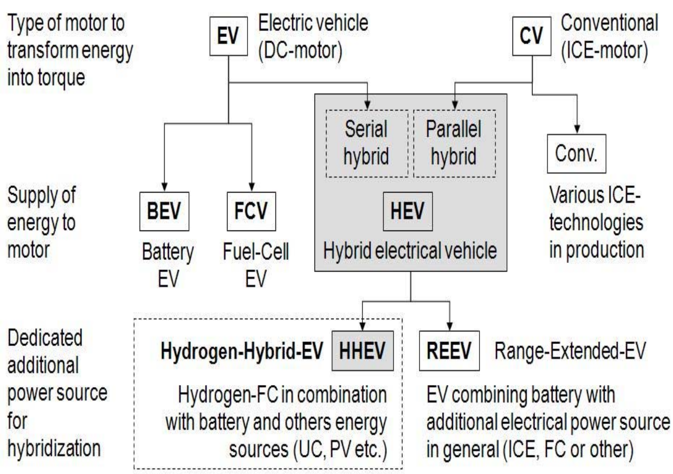

Fig.1 Classification of HEV systems

Several variations and definitions have recently been under some scrutiny for use in alternative car concepts (see Fig.1). Among these vehicles, renewable hydrogen hybrid electric vehicles (HHEV) are considered to be one of the potential alternative candidates to replace conventional fossil fuelled internal combustion engine vehicles. Renewable hydrogen fuel cell vehicles are able to provide better fuel economy and comparatively reduced environmental pollution [2]. By incorporating energy recovery mechanisms, improved performance through energy recovery can be achieved [3]. Energy loss can also be minimized and fuel consumption rate be kept low. In such circumstances, an efficient economic fuel cell vehicle can be realised [3], [4]. The utilization of energy recovery systems makes the hydrogen fuel cell vehicles more attractive by better utilising the on board storage capacity for hydrogen, through raised energy efficiency. Model-based simulation has been used to assist in making an assessment of the benefits from such a system and can be used in exploring further options for improving energy efficiency.

Recent research efforts show that the energy recovery via an active suspension system in hydrogen hybrid electric vehicle may play a part in improving efficiency and extended range capabilities [5], [6]. Energy recovery suspension can achieve a damping function and energy recovery by changing the suspension input vibration produced by road roughness into electrical energy, so removing energy and effecting damping. The control structure of a plausible suspension system is shown in Fig.2. The control unit will detect the available energy supply from the suspension subsystem via the sensors circuit. The recovered energy will then be stored in the vehicle's main electrical energy storage (ESS) such as a battery, to be utilised subsequently to extend the range of the electric vehicle.

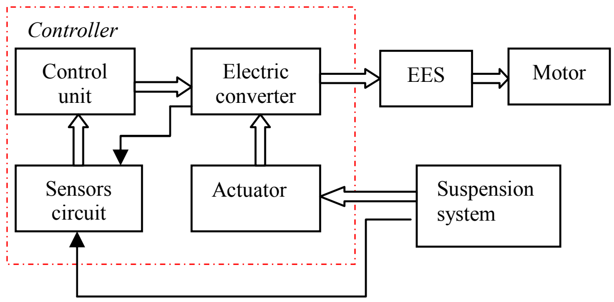

Fig.2 Control operation of a suspension system

Results from previous research show that, significant amount of energy can also be recovered by the integration of the regenerative braking mechanism [4]. Further research effort should focus on the development of a systematic and integrated energy recovery system to recover as much kinetic energy as possible, while maintaining suitable power flows in the other subsystems and effecting a suspension function. To this end, several researchers have developed many different configurations of energy recovery mechanisms to continuously recover energy otherwise dissipated, that results from road irregularities, vehicle acceleration, and braking; see for example [7]-[12]. This recovered energy can be used to reduce fuel consumption.

This work addresses the issues relating to the development of a new mechanism for optimal energy recovery. The main purpose of the paper is to employ a simulation model of a renewable hydrogen fuel cell vehicle together with an optimal energy recovery system (OERS) to carry out simulation analysis to investigate the effect of the OERS.

II. Energy Recovery Systems for HEV

The energy efficiency and driving range of HHEV system can be increased through the development and incorporation of OERS. Many different types of energy recovery system have been developed over the last two decades. These range from electro-hydraulic braking systems (EHBS) to regenerative shock absorbers [13]-[18].

EHBS can be configured in either series or parallel regenerative mode. In a series configuration, the hydraulic control unit manages the brake cylinder pressures, as well as the front-rear axle brake balance. It requires active brake management to achieve total braking to all four wheels. However, it should be noted that in most modern hybrid electric vehicles the regenerative braking system is applied only on the drive wheel, consequently the system has to use thermal/friction braking systems at the same time, to equilibrate the braking. Parallel configuration is less complex because the thermal brakes are used along with energy recovery by the reversible motor/generator. Front and rear brake balance is retained because the thermal brakes are in use during the entire braking event. The amount of energy captured by a parallel regenerative braking system is thus less than from a series system [19].

Hydraulic power assist is another way of managing the energy usage. In the hydraulic power assist, when the driver steps on the brake, the vehicle's kinetic energy is used to power a reversible pump, which sends hydraulic fluid from a low pressure accumulator into a high pressure accumulator. The pressure is created by nitrogen gas in the accumulator, which is compressed as the fluid is pumped into the space the bagged or isolated gas formerly occupied. This slows the vehicle and helps bring it to stop. The fluid remains under pressure in the accumulator until the driver pushes the accelerator again, at which point the pump is reversed and the pressurized fluid is used to accelerate the vehicle.

Regenerative shock absorber mechanisms are a recent development for energy recovery and are essentially regenerative suspension systems technologies. In such regenerative suspension systems, the function is, as in a conventional automotive shock absorber, mechanisms to dampen suspension movements to produce a controlled action that keeps the tire firmly on the road and filters road irregularities for comfort and vehicle integrity. This is normally done by converting the kinetic energy into heat energy, which is then dissipated through the hydraulic oil and cylinder by heat transfer to atmosphere. The power generating shock absorber converts this kinetic energy into electricity through the use of a linear electric generator or other device. The electricity generated by each power generating shock absorber stroke (see Fig.3) can then be combined with electricity from other power generation systems such as regenerative braking and stored in the vehicle's energy storage systems [20].

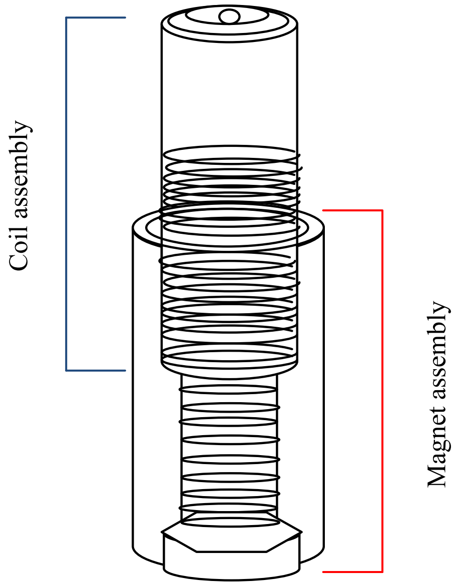

Fig.3 Shock absorbers

For the proposed OERS system, two different energy recovery mechanisms have been considered. These are; the suspension energy recovery mechanism and regenerative braking subsystem. The combined energy recovery sources (suspension energy recovery mechanism and regenerative braking) in the HHEV system may provide a more viable solution if increased capital costs can be rendered economic. The suspension energy recovery mechanism will recover some energy from suspension system and through regeneration from braking, the vehicle is allowed to recapture and store a part of the kinetic energy as opposed to wasting it as heat. Regenerative braking and suspension both essentially convert kinetic energy back into usable energy. Hence, they will be most beneficial in circumstances where most energy is otherwise lost.

III. OERS MODEL

In order to develop an optimal energy recovery system model, it is hypothesised that utilization of a regenerative braking system and an active energy recovery suspension processes in a single system, make the proposed optimal energy recovery system more attractive from an energy system point of view.

Regenerative braking system: In recent literature, hybrid electric vehicle systems, regenerative braking is applied only on the drive wheels, therefore a standard front wheel-drive configuration [21], [22] is adopted in this paper. The regenerative braking operation can be described by the following equations.

The braking force required F_{req} is given by;

$$F_{req} = F_{acc} - F_{roll} - F_{drag} - F_{hill} \tag{1}$$

Where F_{acc} is the force required to give the rate of change of velocity (i.e., acceleration/deceleration), F_{roll} the rolling resistance force, F_{drag} is the aerodynamic drag, F_{hill} is the hill climbing force.

The power required to slow the vehicle P_{req} is calculated by;

$$P_{req} = F_{req} v \tag{2}$$

Where v is the vehicle velocity.

P_{req} is the total power required for the front and rear axles. Thus,

$$P_{req} = P_f + P_r \tag{3}$$

Where P_f and P_r are the power provided by the front and rear wheels respectively. It should be noted that $P_f > P_m$ due to the efficiency of the motor sub-system, where P_m is the motor electric power and is given by;

$$P_m = \eta_m . P_f \tag{4}$$

Where η_m is the efficiency of the motor and is calculated by;

$$\eta_m = \tau_m \omega_m / (\tau_m \omega_m + k_1 \tau_m^2 + k_2 \omega_m + k_3 \omega_m^3 + k_s) \tag{5}$$

Where τ_m is the motor braking torque, ω_m is the motor angular speed, k_1, k_2 and k_3 are the material losses coefficients. k_s is the constant losses that apply at any velocity

The power that charges the battery P_{ch} is given by;

$$P_{ch} = P_m - P_{av} \tag{6}$$

When $P_{ch} < 0$ it becomes the discharge power, where P_{av} is the average power of the accessories, i.e., the electric power needed to run the other electrical systems. While the HHEV is in motion; when braking is applied, a certain amount of power is dissipated into the battery. In this paper an internal resistance battery model [5] is adopted, which characterizes the battery with a voltage source and an internal resistance.

Let the current I be flowing into the battery, so the charge power of the battery can be obtained as;

$$P_{ch} = EI + I^2 R \tag{7}$$

Where E is the open circuit voltage, and it changes with the state of charge (S) of the battery, R is the internal resistance of the battery. Now, the charge current I is obtained by solving equation (7) and is given by;

$$I = (-E + \sqrt{E^2 + 4RP_{ch}})/2R \tag{8}$$

and (S) is represented as follows;

$$(S) = (S_0) + \Delta t \times I . C_P^{-1} \tag{9}$$

Where (S_0) is the battery initial state of charge, Δt is the sampling time and C_P is the Peukert capacity.

The regenerated power of the battery is calculated as;

$$P_{regen} = P_{ch} - I^2 R \tag{10}$$

With the regenerated energy efficiency η_{regen} defined as;

$$\eta_{regen} = \frac{\int P_{regen}}{\int P_{req}} \tag{11}$$

From the above regenerative braking system (RGBS) model it is clear that the amount of regenerated brake energy depends on multiple factors in HHEV.

Suspension energy recovery system: Energy recovery suspension processes can achieve a significant amount of energy recovery by converting suspension vibration damping required for road roughness, into electrical energy. Design studies of suspension energy recovery systems for hybrid electric vehicles have been conducted recently by several researchers, see for example, [3], [6]. Hybrid electric vehicle configuration with active suspension systems would allow the recovery of energy and hence, lead to the extended range capabilities. The purpose of a suspension system is to support the vehicle body, damp vibration and increase ride comfort. Currently, there are three different types of suspension systems used in automobile industry: passive, semi-active and active [6]. The traditional passive suspensions use springs and dampers to absorb the oscillation while in active cases the suspension is controlled by an external controller. Semi-active suspensions include devices such as springs and shock absorbers together with other systems such as hydro-pneumatic and electromagnetic suspension. On the one hand, the use of semi-active/active suspension achieves a better isolation performance for various vibration modes and improves the riding comfort, but on the other hand, they increase the cost, weight and energy consumption of the car. The suspension energy recovery mechanism developed here is expected to recovery some energy from the suspension system to improve the energy efficiency. The dynamic model with seven degree of freedom (7-DOF); four wheel suspension systems can be expressed using differential equations [5]. Fig. 4 shows a simplified version of a suspension system for a complex full car model.

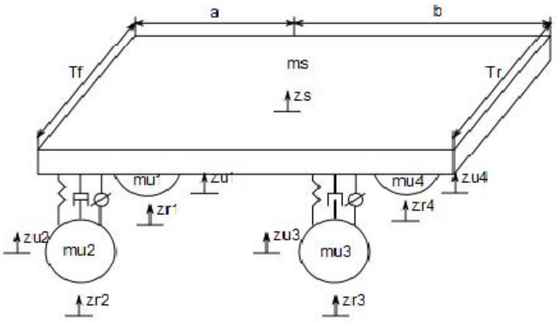

Fig.4. Simplified version of a suspension system for a complex full car model

There are roll, pitch and vertical displacement of sprung mass and four unsprung mass are included. The dynamic model is divided into seven main parts:

Bouncing of the sprung mass

$$\begin{aligned} m_s\ddot{Z}_s = &-b_f\left(\dot{Z}_{s_1}-\dot{Z}_{u_1}\right)-bf\left(\dot{Z}_{s_2}-\dot{Z}_{u_2}\right)-br\left(\dot{Z}_{s_3}-\dot{Z}_{u_3}\right)\\ &-br\left(\dot{Z}_{s_4}-\dot{Z}_{u_4}\right)-kf\left(Z_{s_1}-Z_{u_1}\right)-kf\left(Z_{s_2}-Z_{u_2}\right)\\ &-kr\left(Z_{s_3}-Z_{u_3}\right)-kr\left(Z_{s_4}-Z_{u_4}\right)+u_1+u_2+u_3+u_4 \end{aligned} \tag{12}$$

Pitching of the sprung mass

$$\begin{aligned} I_p\ddot{\theta}_s = &-b_f a\left(\dot{Z}_{s_1}-\dot{Z}_{u_1}\right)-b_f a\left(\dot{Z}_{s_2}-\dot{Z}_{u_2}\right)-b_r b\left(\dot{Z}_{s_3}-\dot{Z}_{u_3}\right)\\ &+b_r b\left(\dot{Z}_{s_4}-\dot{Z}_{u_4}\right)-k_f a\left(Z_{s_1}-Z_{u_1}\right)+k_f a\left(Z_{s_2}-Z_{u_2}\right)\\ &+k_r b\left(Z_{s_3}-Z_{u_3}\right)+k_r b\left(Z_{s_4}-Z_{u_4}\right)+au_1+au_2-bu_3-bu_4 \end{aligned} \tag{13}$$

Rolling of the sprung mass

$$\begin{aligned} I_r\ddot{\varphi}_s = &-b_f T_f\left(\dot{Z}_{s_1}-\dot{Z}_{u_1}\right)-b_f T_f\left(\dot{Z}_{s_2}-\dot{Z}_{u_2}\right)-b_r T_r\left(\dot{Z}_{s_3}-\dot{Z}_{u_3}\right)\\ &+b_r T_r\left(\dot{Z}_{s_4}-\dot{Z}_{u_4}\right)-k_f T_f\left(Z_{s_1}-Z_{u_1}\right)+k_f T_f\left(Z_{s_2}-Z_{u_2}\right)\\ &-k_r T_r\left(Z_{s_3}-Z_{u_3}\right)+k_r T_r\left(Z_{s_4}-Z_{u_4}\right)+T_f u_1-T_f u_2+T_r u_3-T_r u_4 \end{aligned} \tag{14}$$

Vertical direction for each wheel

$$m_{uf}\ddot{Z}_{u_i} = b_f\left(\dot{Z}_{s_i}-\dot{Z}_{u_i}\right)+k_f\left(Z_{s_i}-Z_{u_i}\right)-k_{tf}Z_{u_i}-u_i+k_{tf}Z_{r_i} \tag{15}$$

with $i=1,2,3,4$

where;

$$Z_{s_1} = T_f\varphi_s + a\theta_s + Z_s,\ \dot{Z}_{s_1} = T_f\dot{\varphi}_s + a\dot{\theta}_s + \dot{Z}_s$$

$$Z_{s_2} = -T_f\varphi_s + a\theta_s + Z_s,\ \dot{Z}_{s_2} = -T_f\dot{\varphi}_s + a\dot{\theta}_s + \dot{Z}_s$$

$$Z_{s_3} = -T_r\varphi_s - b\theta_s + Z_s,\ \dot{Z}_{s_3} = -T_r\dot{\varphi}_s - b\dot{\theta}_s + Z_s$$

$$Z_{s_4} = -T_r\varphi_s - b\theta_s + Z_s,\ \dot{Z}_{s_4} = -T_r\dot{\varphi}_s - b\dot{\theta}_s + \dot{Z}_s$$

where Z_s is the vertical displacement, Z_{u_i} $(i=1,2,3,4)$ is the vertical displacement of each wheel, θ_s pitch angle and φ_s roll angle.

So far, a regenerative braking system model and a suspension system for a complex full car model have been established. These models are then used for the design of a combined OERS system to improve HHEV performance.

The combined OERS system is implemented in MATLAB/Simulink™ and incorporated into a vehicle simulator [5] to analysis the effect of the integration of the OERS system. In the following section of the paper discusses results from the OERS system developments.

IV. Results and Discussion

The simulation results show that by using this combined optimal energy recovery mechanism, a considerable amount of energy can be recovered. For illustrative purposes, example simulation results are shown here. For this simulation, the New European drive cycle (NEDC) (see Fig.5) is used here and the suspension system parameters are listed in Table 4.1.

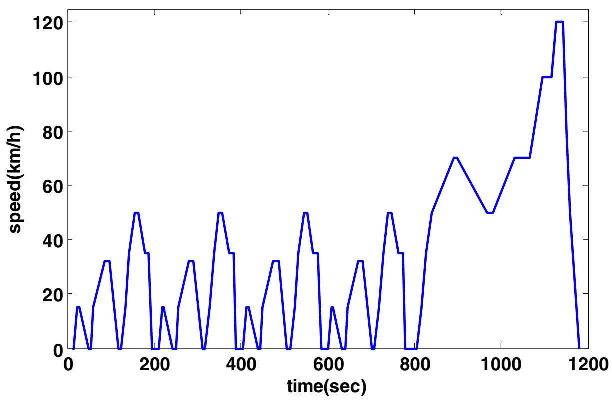

Fig.5 New European Drive cycle

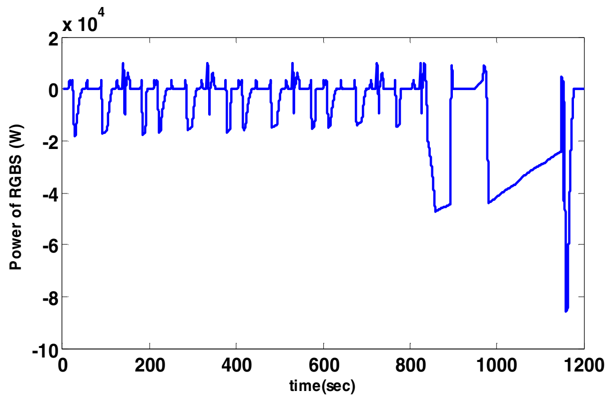

Fig.6 Power of RGBS energy recovery

Table 4.1: Suspension system parameters

Symbol	Quantity	Unit
Suspension system parameters		
m_s	464	Kg
m_u	35	Kg
K_s	16812	N/m
K_t	190000	N/m
b_s	1000	N/m
b_t	1000	N/m

where m_s is the mass of a vehicle, m_u is the mass of a wheel components, K_s is the spring stiffness, K_t is the tire stiffness, b_s is the damper coefficient, and b_t is the tire damping coefficient.

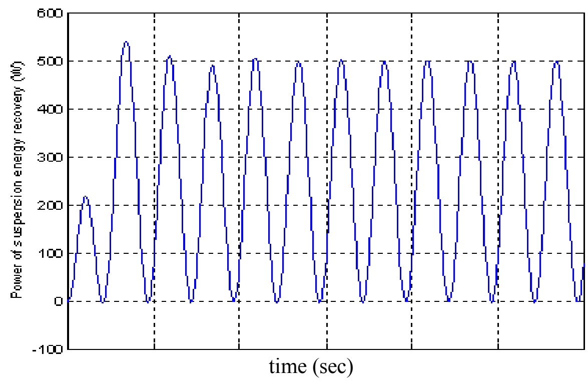

Fig.7 Power of suspension energy recovery

Suppose, the energy recovered by the use of the suspension energy recovery mechanism is used to produce hydrogen, then the average hydrogen production rate is about $4\times10^{-3}kgh^{-1}$ (see Fig.8).

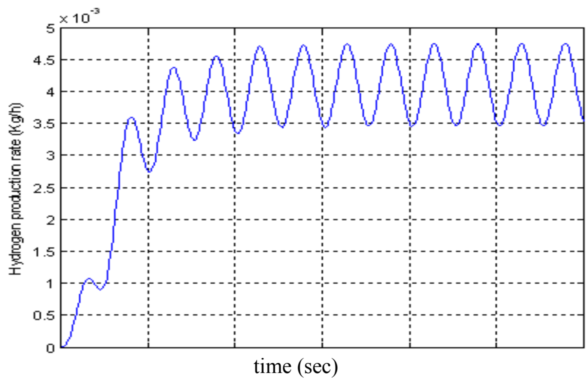

Fig.8 Hydrogen production rate from the suspension energy recovery mechanism

Fig. 6 and 7 shows the power of RGBS energy recovery and power of suspension energy recovery respectively. From the results it is clearly shown that the RGBS recover more energy than the suspension energy recovery system. However, it should be noted that the total energy recovered by the use of OERS is higher than using only the suspension recovery mechanism or RGBS (see Fig.9 and 10). In Fig. 9 the total energy recovery by the OERS is shown. Figure 10 shows the enlarged view of compared responses of Fig.6 and 9 for the first 30 sec in order to clearly show the power of OERS (solid line) and RGBS (dashed line).

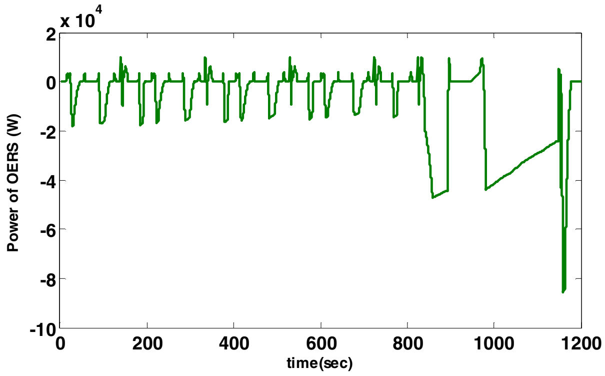

Fig.9 Power of OERS system

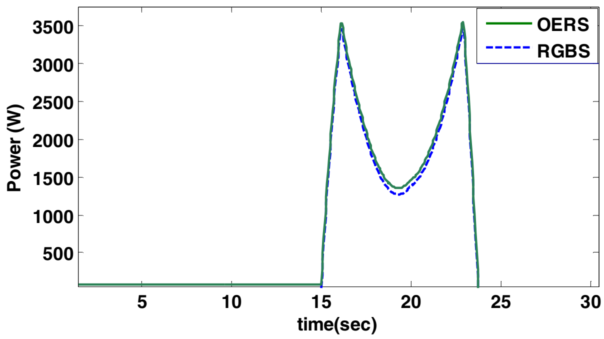

Fig.10 Comparison of power of OERS and RGBS

V. CONCLUDING REMARKS

In this paper, an investigation of the development of an optimal energy recovery system for a renewable hydrogen fuel cell vehicle is carried out. A dynamic model of a regenerative braking system and an active suspension energy recovery system has been developed and combined as a single energy recovery mechanism. This optimal energy recovery subsystem is implemented in MATLAB/Simulink^{TM}. The model is then incorporated into a vehicle simulator to analysis the effect of the integration of the energy recovery mechanism. The results show that by using this mechanism, significant amount of energy can be recovered. It is expected that the modelling will provide a suitable platform for investigating the effects of system architecture and vehicle drive cycles analysis.

ACKNOWLEDGMENT

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REFERENCES

[1] KKT. Thanapalan and GP. Liu, "Modelling and control of fuel cell hybrid electric vehicle systems", *In the Proc of the UKACC Int. Conference on Control, Coventry, UK,* pp.1100-1105, 2010.
[2] A. Emadi., ad SS.Williamson "Fuel cell vehicles: opportunities and challenges," in *the Proc. IEEE Power Engineering Society General Meeting*, *Denver, Colorado, USA*, vol.2, pp. 1640–1645, 2004.
[3] KKT. Thanapalan, F. Zhang, AD. Procter, SJW. Carr, GC. Premier, AJ Guwy, and J. Maddy "Development of energy saving mechanism for renewable hydrogen vehicles", *Renewable Energy and Power Quality Journal*, vol.1, No.10, 353, 2012
[4] F. Wang, and B. Zhuo "Regenerative braking strategy for hybrid electric vehicles based on regenerative torque optimization control", *Journal of Automobile Engineering*, vol.222, pp.499-513, 2008
[5] KKT. Thanapalan, F. Zhang, GC. Premier, J Maddy and AJ. Guwy "On-board renewable hydrogen production system for hydrogen hybrid vehicles", *In the Proc. of the World Renewable Energy Congress, Denver, Colorado, USA.* 2012
[6] R. Rajamani, and KJ. Hedrick, "Adaptive observers for active automotive suspensions theory and experiment", IEEE Transactions on control systems technology, vol.3, No.1, 1995
[7] H. Yeo, S. Hwang, and H. Kim, "Regenerative braking algorithm for a hybrid electric vehicle with CVT ratio control", *Proceedings of the Institution of Mechanical Engineering, Part D: Journal of Automobile Engineering,* vol.220, pp.1589-1600, 2006
[8] J. Zhang, X. Lu, J. Xue, and B. Li, "Regenerative braking system for series hybrid electric city bus", *The World Electric Vehicle Journal*, vol.2, No.4, pp.128-134, 2008
[9] J. Yao, Z. Zhong, and Z. Sun, "A Fuzzy logic based regenerative braking regulation for a fuel cell bus" *In the Proc of the IEEE International Conference on Vehicular Electronics and Safety*, pp.22-25, 2006
[10] SR. Cikanek and KE. Bailey, "Regenerative braking system for a hybrid electric vehicle", *In the Proc of the American Control Conference, Anchorage, AK, USA*, pp.3129-3134, 2002
[11] KT. Chau and YS. Wong, "Overview of power management in hybrid electric vehicles", *Energy Conversion and Management*, vol.43, pp.1953-1968, 2002
[12] J. Paterson, and M. Ramsay, "Electric vehicle braking by fuzzy logic control, *IEEE Industry Applications Society Annual Meeting*, pp2200-2204, 1993
[13] M. Assaf, D. Seshsachalam, D. Chandra, and RK Tripathi, "DC-DC Converters via MATLAB/Simulink", *In the Proc of WSEAS Conference on Automatic Control, Modelling and Simulation (ACMOS'05), Prague, Czech Republic*, pp.464-471, 2005
[14] JD. Halderman, "Automotive brake system" 5th Edition, Pearson Education Inc., Prentice Hall, USA, 2010
[15] D. Prokhorov, "Toyota Prius HEV Neurocontrol and diagnostics", *Neutral Networks*, vol.21(3), pp.458-465, 2008
[16] MH. Rashid (Ed), "Power Electronics handbook: Devices, circuits, and applications", 3rd Edition, Elsevier Inc., 2011
[17] B. Cao, Z. Bai, and W. Zhang, "Research on control for regenerative braking of electric vehicles", *In the Proc of the IEEE International Conference on Vehicular Electronics and Safety*, pp.92-97, 2005
[18] Y. Gao, L. Chen, and M. Ehsani, "Investigation of the effectiveness of regenerative braking for EV and HEV", SAE Technical paper 1999-01-2910, 1999
[19] Electro-Hydraulic Brake System (EHBS), www.autoelectronics.com, 2012
[20] shock absorber, www.gizmag.com, 2012
[21] L. James, and L. John, "Electric vehicle technology explained", England, UK: John Wiley & Sons, pp183-292, 2003
[22] J. Guo, J. Wang, and B.Cao, "Regenerative braking strategy for electric vehicles", *In the proc of the IEEE Intelligent vehicles symposium*, pp864-868, 2009