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Energy Management Effects of Integrating Regenerative Braking into a Renewable Hydrogen Vehicle

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Abstract—**This paper discusses the design and route to implementation of a regenerative braking system for a Renewable Hydrogen Hybrid Electric Vehicle (RHHEV) that would performs regenerative energy recovery based on vehicle attributes, thereby providing improved performance. A dynamic model of a regenerative braking system for a RHHEV has been derived and implemented in MATLAB/Simulink. The model is then incorporated into a simulation model of a RHHEV to analyze the energy management effects of integrating the regenerative braking into the system. Simulations are carried out and the results are discussed in this paper. The results indicate that this approach provides an improvement in performance and fuel efficiency to the RHHEV system.**

Keywords – Hydrogen vehicles, Renewable energy, Regenerative braking, Energy sources, Energy recovery

I. INTRODUCTION

The utilization of regenerative braking (RB) makes the hydrogen fuel cell vehicles more attractive by better utilising the on board storage capacity for hydrogen, through raised energy efficiency. RB systems could recover the energy that would otherwise be lost through braking [1]. The results from previous research efforts show that, significant amount of energy can be recovered by the integration of a regenerative braking mechanism [2]. Further research effort should focus on the development of a systematic and integrated regenerative braking system to recover as much energy as possible, while maintaining suitable power flows in the other subsystems. To this end, several researchers have developed many different configurations of energy recovery mechanisms to continuously recover otherwise dissipated energy that occurs due to road irregularities, vehicle acceleration, and braking; see for example [3]-[9].

In this paper, developments in energy recovery mechanisms for renewable hydrogen hybrid electric vehicle (RHHEV) systems are described. Essentially and in general terms there are two approaches to such energy recovery mechanisms; implementation of a better energy management system by providing optimal powertrain topologies applied to the various energy sources and incorporating an energy recovery mechanism [10]. This work addresses both approaches by describing an optimal power management strategy for RHHEV systems for better energy management and the development of a regenerative braking system (RBS) for energy recovery. This paper begins with a discussion of RB techniques and this is followed by the incorporation of the RB system into an optimal power management strategy for RHHEV and analyses.

II. REGENERATIVE BRAKING SYSTEM

The energy efficiency and driving range of the RHHEV system may be increased through the development and incorporation of RBS. The regenerative braking methods have the capability to increase hybrid electric vehicle (HEV) driving range by approximately10-30% [11]. Further benefits of RBS are that they can reduce the drawdown of battery charge, extend the overall life of the battery pack and reduce fuel consumption. However, the main problem with RBS is that at low speed, the electric motor may not be able to produce enough torque to stop the vehicle [12], [13]. The goal of the RBS is to recover some of the energy otherwise wasted as braking heat and store it, and then later use it for vehicular motion. The principle of a RBS circuit is shown in Fig.1. This is commonly known to represent the conditions for four quadrants of possible operation for the regenerative braking [14], [15].

In forward motoring (quadrant I) v_a , E_g , and I_a are all positive. The torque and speed are also positive in this quadrant. During forward braking (quadrant II), the motor runs in the forward direction and the induced emf E_g will continue to be positive. For the torque to be negative and the direction of the energy flow to reverse, the armature current must be negative. The supply voltage v_a should be keep less than E_g . In reverse motoring (quadrant III), v_a , E_g , and I_a

are all negative. The torque and speed are also negative in this quadrant. To keep the torque negative and the energy flow from the source to the motor, the back emf E_g must satisfy the condition $|v_a| > |E_g|$.

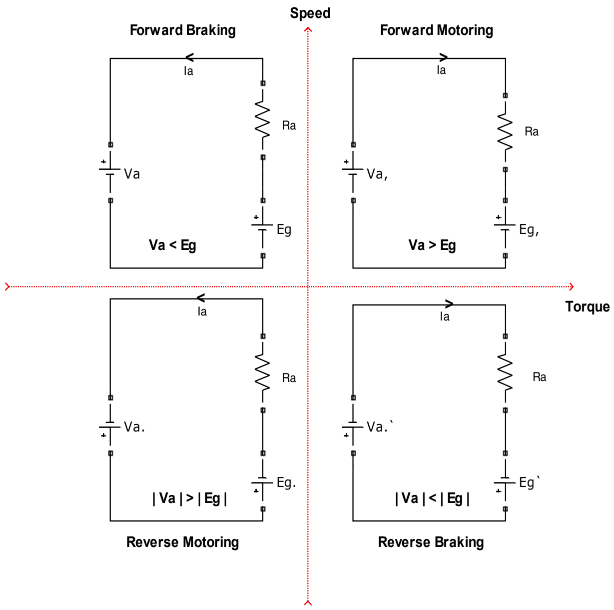

Fig.1 Principle of RBS

The polarity of E_g can be reversed by changing the direction of field current or by reversing the armature terminals. During reverse braking (quadrant IV), the motor runs in the reverse direction. v_a and E_g will continue to be negative. For the torque to be positive and the energy to flow from the motor to the source, the armature current must be positive. The induced emf E_g must satisfy the condition $|v_a| < |E_g|$.

Using this fundamental principle, there are many different types of energy recovery system that have been developed. These range from electro-hydraulic braking (EHB) systems to energy harvesting shock absorber [16]-[20]. In this paper, a simulation model of a simple regenerative braking system is developed and implemented in MATLAB/Simulink™ and incorporated into a vehicle simulator previously developed [21] to analyse the effect of integrating the RBS. The vehicle model used here is for the University of Glamorgan hydrogen bus (UoGHB). The powertrain of UoGHB consist of 12kW PEM fuel cell stack developed by Hydrogenics, a 288v, 132 Amp-hr battery pack, 375v, 63F Maxwell ultracapacitor and 70kW DC motor. Simulations are carried out on the New European Drive Cycle (NEDC) shown in Fig.2.

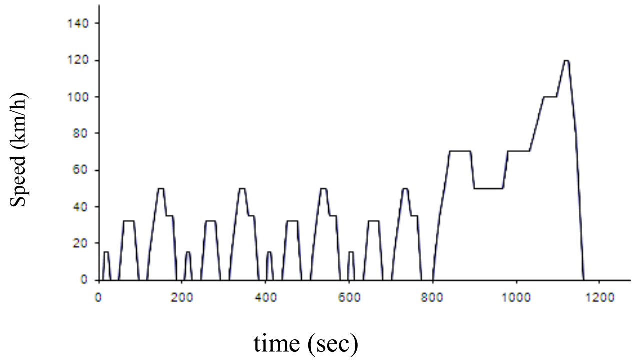

Fig.2 New European Drive Cycle

The combined power sources (fuel cell, battery and ultracapacitor) in a RHHEV provide a more viable solution than a single power source renewable vehicle [10]. The fuel cell system provides low to medium constant power delivery, whereas the lead acid battery pack provides medium constant power. Finally the ultracapacitors (UC) deliver a large, instantaneous power demand, which is ideal for high load acceleration and regeneration from braking power [22].

The regenerative braking is only possible, if there is enough torque applied to the wheels, in accordance with the driving conditions. These requirements may be expressed in and governed by the following equations [2], [5], [6]:

The regenerative torque applied to the front wheels τ_R is given by;

$$\tau_R = \eta\phi\tau_{RB} \quad (1)$$

Where, η is the efficiency, ϕ is the continuously variable transmission speed ratio and by considering that the motor has a reversible performance characteristic curve; τ_{RB} is the regenerative torque provided by the motor which is determined from the motor characteristic curve for the given speed [2] and is described as follows;

$$\tau_{RB} = \varpi_f(b_{soc}, v)\tau_m \quad (2)$$

Where, ϖ_f is the weighting factor and it depends on the battery state of charge b_{soc} and vehicle velocity v. τ_m is the electric motor torque. The regenerative braking force at the wheels F_{RB} is obtained as;

$$F_{RB} = \tau_R . r_t^{-1} \quad (3)$$

Where, τ_R is the regenerative torque applied to the front wheel, r_t is the tyre radius and F_{bf} is the required front wheel braking force. If $F_{RB} > F_{bf}$ then the front wheel is braked only by the regenerative brake. Otherwise the regenerative braking needs to be combined with conventional friction braking. Suppose, the hydraulic friction brake works with the regenerative brake, then in this case the change in hydraulic pressure in the front wheel cylinder ΔP is given by;

$$\Delta P = \tau_{RB}(\lambda A \times 2r_e)^{-1} \quad (4)$$

Where, λ is the friction coefficient, A is the front wheel cylinder area and r_e is the effective radius. So, the supplied hydraulic pressure P_h is calculated as;

$$P_h = P_s - \Delta P \quad (5)$$

Where, P_s is the master cylinder pressure. Finally, the total braking torque τ_{BK} at the front wheel is given by;

$$\tau_{BK} = \tau_R + \tau_{fr} \quad (6)$$

Where, τ_{fr} is the torque provided by conventional friction braking.

From the above analyses it is clear that the amount of regenerative brake energy depends on available motor torque, which will vary according to battery state of charge (SOC), motor speed and corresponding driver demands. It is desirable that the system use the least possible stored energy to provide the required motive or ancillary demands. This can be achieved by using energy saving mechanisms or power management algorithms [23]. Therefore, in this paper an optimal power management strategy is also integrated into the configuration of a RHHEV system with RBS. The system analyses and performances are described in the following sections.

III. Power Management of RHHEV with RBS

RHHEV has become increasingly of interest in the powertrain industry due to the finite supply of fossil fuels and the effects fossil fuels are having on the environment [10]. Hybrid electric vehicle (HEV) developments play an important role in the realisation of the renewable hydrogen hybrid electric vehicles. CO_2 emission reduction and possible fuel economy benefits are attractive functions of HEV systems. RHHEV's are expected to make a significant contribution to the environmental needs/demands of the premium vehicle sector. However, combining a polymer electrolyte membrane fuel cell (PEM FC) stack, UC module, with a battery pack; while managing power flow and meeting the high expectations of the market, presents challenges in the area of system configuration and controller design [10]. The system configuration and controller design for HEV systems can be complex and challenging. The control system design requires a high level of integration with existing systems on the vehicle.

The literature contains several publications concerning various aspects of HEV system power distribution methodologies and controller design; see for example, [9], [18], [19]. Broader details of the subject can be found in various reports, which summarise the power management aspects and problems experienced with HEV [22]-[24]. These reports also suggest some technical solutions and analytical methods for application to some of the problems. These range from control algorithms for global optimization, based on *a priori* knowledge of a scheduled driving cycle, to real-time power management based on optimal control theory [23].

Previous power management design efforts focussed on the design methods to determine the component sizes that minimized the cost of the power system elements in HEV [25]. Furthermore, power management strategies and component sizing are often coupled together, which implies that different component sizing might be associated with different power management strategies. Therefore both should be considered as a combined package. Many other research efforts on power distribution in HHEV have been expanded. These include; the use of an equivalent consumption minimization strategy to determine the real time optimal power distribution of a fuel cell/UC hybrid vehicle [26]. In this study, an optimal power management strategy for HHEV systems described in [23] is adopted and integrated with the RBS, in order to maximize the benefit of the RBS. The power source configuration of the RHHEV is shown in Fig.3.

The DC-link is the connection mechanism between the electrochemical power source and the motor. The DC-link is kept at a constantly high voltage, thereby assuring the highest possible motor torque over the whole speed range. Since the voltage of the power sources may vary, a DC/DC converter is needed in the configuration (see Fig.3).

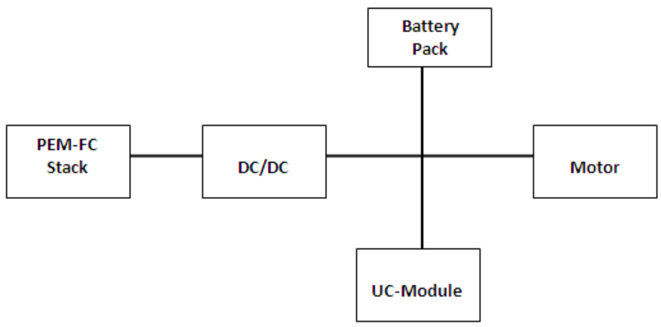

Fig.3 Power source configuration of a HHEV system

The power balance equation for the overall RHHEV system is given by;

$$p_{fc} + p_{uc} + p_b = p_d \quad (7)$$

where p_{fc}, is the output power of the PEM fuel cell stack, p_{uc}, the output power of the ultracapacitor, p_b the output power of the battery pack and p_d, the power demand. The regenerated power of the battery is calculated as;

$$p_{RB} = p_b - i^2 R \quad (8)$$

The combined system with RBS and optimal power management (PM) is implemented in MATLAB/Simulink™ and simulated using the UoGHB vehicle simulator [21].

IV. Results and Discussion

The simulation results show that by using this regenerative braking (RBS) mechanism with an optimal power management strategy, a considerable amount of energy can be recovered. The results indicate that the combined optimal power management strategy with RBS has significantly improved the RHHEV system efficiency and total power recovery.

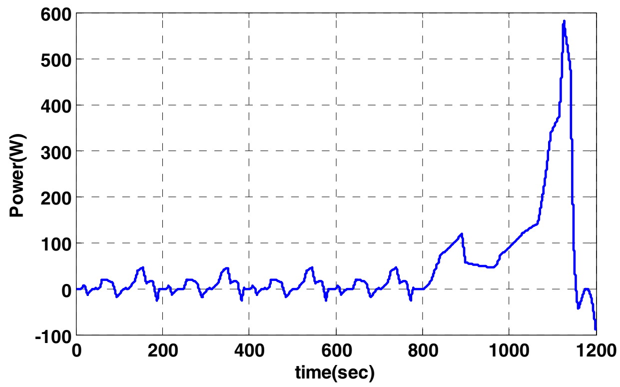

Fig.4 power requirements

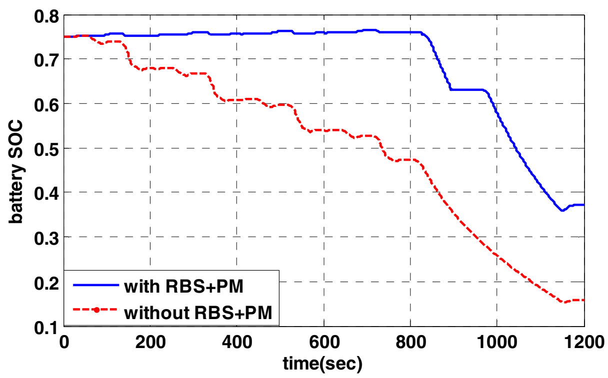

Fig.5 Compared responses of battery SOC

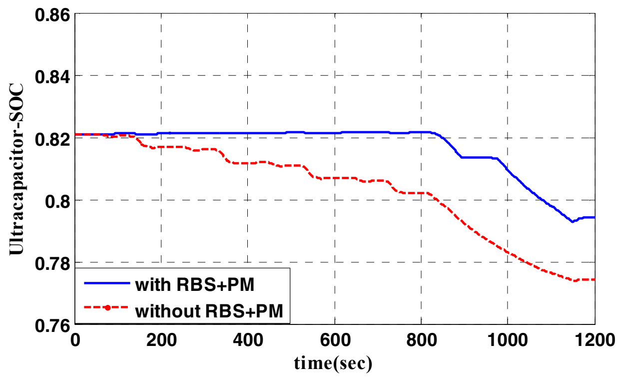

Fig.6. Compared responses of Ultracapacitor- SOC

In Fig.4 the total power requirements for the whole NEDC is shown. The combined power sources (battery, ultracapacitor and fuel cell) will provide the power to RHHEV for the required driver demand. Fig.5 & 6 shows a comparison of the charge/discharge characteristics of battery pack SOC and ultracapacitors respectively. It may be realised from these results that, due to the regenerative energy recovery and the inclusion of the optimal power management strategy the state of charge of these power sources are kept high (apart from at higher power demand) and able to provide constant power. The energy required in any given HEV system depends on the systems design and operation characteristics and the quantity and type of losses encountered during vehicular motion. In this paper the energy requirement for the HHEV system is analysed with reference to the UoGHB. The system model includes the regenerative energy recovery mechanism, thus it is of interest from an energy system point of view. It is therefore, essential to search for design and operating conditions which lead to reduction of energy dissipation and consequently lower production cost to promote the HHEV system. To this end, the UoGHB model is used to show the improvement of energy consumption via system analysis, which includes the regenerative energy recovery and power management.

Summary of energy consumption for both cases (with and without RBS plus PM) are shown in Table 4.1. In energy terms the maximum energy capacity of the battery pack and UC modules installed in the UoGHB is 38.3 kWh and 1.2 kWh respectively and energy capacity of the hydrogen fuel tank is 33.28 kWh. Usually battery/UC states of charge are kept to particular limits (or constant) to increase the life of the battery. This leads to variable usage of hydrogen and it can be controlled by incorporating an optimal control algorithm and energy saving mechanisms. In this paper for the simulation analysis, the NEDC is used and at the start of the journey it is assumed that the hydrogen tank is full and the battery SOC and UC-SOC are at 75 and 82 % respectively (see Fig.5 & 6). In energy term this is about 28.73 kWh and 0.98 kWh respectively. If the RBS and PM are not included, at the end of the journey, energy left in the battery is about 6.32 kWh (16%) and in UC is about 0.92 kWh (77%). With the inclusion of the RBS and PM the energy remaining in battery and UC is about

13.98 kWh (37%) and 0.94 kWh (79%) respectively. However, the hydrogen fuel usage was high in comparison with the system without RBS and PM. This is due to the arrangements of power management and system configuration. In this case the FC-stack is considered to be the main power source to supply the power. But, it should be noted that overall a significant improvement is achieved in energy saving by incorporating RBS and PM. The improvement is about 4.9 kWh energy saving. Thus, the system efficiency is improved by about 27%.

Table 4.1 summary of energy consumption

Start of ride	Energy	after - without RBS+PM		after - with RBS+PM		
75%	28.73	16%	6.32	37%	13.98	better
		0.01	consumption	0.095	consumption	
1	33.28	0.986	32.81	0.905	30.12	worse
82%	0.98	77%	0.92	79%	0.94	better
	62.99		**40.05**		**45.04**	kWh
				improvement	**4.99**	kWh

The energy consumption in any HEV system is one of the important parameters that dictate the choice of the HEV. In addition to the energy consumption the cost of the technology and the final cost of the vehicle determine the choice of the HEV system.

V. Concluding Remarks

In this paper, an investigation of the development of a RBS with an optimal PM strategy for a RHHEV system was carried out. A dynamic model of a RBS with an optimal PM strategy has been described and implemented in MATLAB/Simulink. The model was then incorporated into a UoGHB simulator to analyse the effect of the integration of the regenerative braking mechanism. The results show that if such mechanisms are used in the UoGHB, about 4.9kWh energy could be saved during the whole NEDC. Thus, it can be concluded that in general using such a mechanism in any HHEV system is likely to a significant amount of energy being recovered.

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