Design of Regenerative Braking System for an Electric Vehicle (EV) Modified from Used Car

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Abstract

In general one of the main objectives of regenerative braking system is to recover as much as possible kinetic energy while braking instead of being dispersed in form of heat by only friction brake. In Electric Vehicle (EV) with regenerative braking system, most braking energy is converted to electrical form via generator switched from its motor, and stored in storage device or battery to use in vehicle's electric application or use to propel itself. Thus, the EV with regenerative braking system can extend driving range. In this study, a prototype of the EV is modified from an internal combustion engine vehicle. The regenerative algorithm and equipment, based on a conventional braking system of this EV, are presented and its functional validation is investigated by using numerical simulation. Regarding the braking torque distribution between regenerative and friction brake, the available regenerative torque from electric motor is computed depending on current vehicle velocity, the torque characteristic of the motor-generator, and the state of charge (SOC) of the Li-Ion batteries**.** The friction brake torque of driven wheels, front wheel, will be reduced equal to regenerative torque by reducing brake fluid pressure. To determine the regenerative system efficiency, three regenerative strategies are investigated: non-modified braking system, modified braking system with emulated ABS signal, and modified braking system with brake fluid distribution in master cylinder. In this study, the criteria for analyzing these regenerative systems are energy recovery, and braking performance represented by braking distance. The simulated results indicate that the regenerative strategy of modified braking system with emulated ABS signal is the most proper in this study.

Key words**:** Regenerative braking system, Electric vehicle (EV)

1. Introduction

Since the crisis of the price of fossil oil on the world market rising higher almost every time directly affects to Thailand, making most vehicle users turning the behavior to utilize low-priced alternative energy such as Gasohol, Biodiesel, Liquid Petroleum Gas (LPG) or Compressed Natural Gas (CNG). Especially, LPG and CNG are mostly popular because of their cheap prices per unit and the inexpensive budget of installation. However, the concerns about emission problem like carbon dioxide quantity or greenhouse effect still continuously take place. One of the measures of reducing traffic emission is to propel to use natural friendly vehicles for instance Battery electric vehicle (BEV). Since EV is still expensive and not widespread, the expected tendency of using the EV in Thailand should be alike the utilization LPG or CNG being alternative energy in that the conventional internal combustion engine used cars are modified to be EV.

Regenerative braking system is a significant part of EV, which is responsible for recovering potential and kinetic energy during vehicle braking and storing it into energy storage device instead of dissipating in heat form by fiction brake. The stored energy is utilized to propel vehicle [1] or to supply vehicle's electrical application. Regenerative braking system is an effective means to prolong the driving range of EV and also to improve fuel consumption rate of Hybrid Electric Vehicle (HEV), particularly for the vehicle that mainly runs in high frequent stop and go condition such as city traffic [2]. The past researches have suggested that an HEV's driving range in urban can be extended between 14 and 40% by using regenerative brake [3], [4].

In general, the regenerative braking system is collaborated with the conventional friction brake because of following reasons. The first one is that the available brake torque of motor-generator, while emergency braking occurs, is not large enough to fulfill such huge braking requirement. The second reason is that in such condition as high voltage of the energy storage component, high state of battery's charge (SOC), or high temperature to damage battery, regenerative brake cannot be operated since the reason of the damage to battery [5].

Some relevant reports of regenerative braking system that have been proposed are presented. Y.Gao et. al. [6] suggests the regenerative model and algorithm for EV and HEV focusing on vehicle stability by controlling brake force between front and rear wheels. M.Pabagiotidis et. al. [7] proposes controlling algorithm and regenerative model using specific simulation software. This algorithm relies on Look-up table to provide brake force distribution into front and rear wheels as well as generator. H.Yeo et. al. [8] proposes hydraulic braking module for regenerative braking system and algorithm for controlling regenerative braking module and continuously variable transmission (CVT). Nevertheless, all above regenerative systems are designed for front/rear split circuit braking system that cannot be applied for a passenger car with cross link circuit braking system.

The objective of this paper is to determine the most proper regenerative system for an EV modified from used car equipped with cross link circuit braking system and anti-lock brake system (ABS). In this study, a total of three strategies are proposed. The difference of each model is the method of controlling the brake fluid distribution into the regenerative and the mechanical braking system. The performance of each strategy is executed by numerical simulation. The design criteria are regenerative energy and braking performance represented by braking distance.

2. Regenerative braking strategy

The layout of internal combustion engine (ICE) vehicle and electric vehicle are shown in Figure 1 and 2 respectively. The platform of this ICE vehicle is front engine, front drive (FF) using manual transmission. Its braking system is cross link circuit or X layout with four wheel disk brakes and anti-lock brake system (ABS). The modification from engine into electric vehicle is achieved by installing motor-generator (MG) instead of engine and changing the manual transmission into fixed transmission since electric motor does not need complex-ratio transmission so as engine to maintain optimal operation on the fuel economy region. Thus, this vehicle platform is still the FF, front motor, front drive. Because regenerative torque needs medium to send this brake torque into driven wheel, the vehicle platform is factor defining that only driven wheel, front wheel in this case, can contribute regenerative braking power. Therefore, front wheels are cooperated by regenerative and friction brake force while rear wheels have only friction brake operation.

2.1 Non-modified braking system

Based on this regenerative strategy, shown in figure 2, conventional braking system is applied without modification. During braking, the mechanical braking system is operated independent of regenerative process. In this case, the pressure of brake fluid at front wheel remains as conventional. Thus, while regenerative brake operates at front wheels, the amount of front brake force is higher than normally required brake force. Nevertheless, the concern about front wheel locking is resolved by ABS that automatically reduces brake pressure if wheel locking takes place.

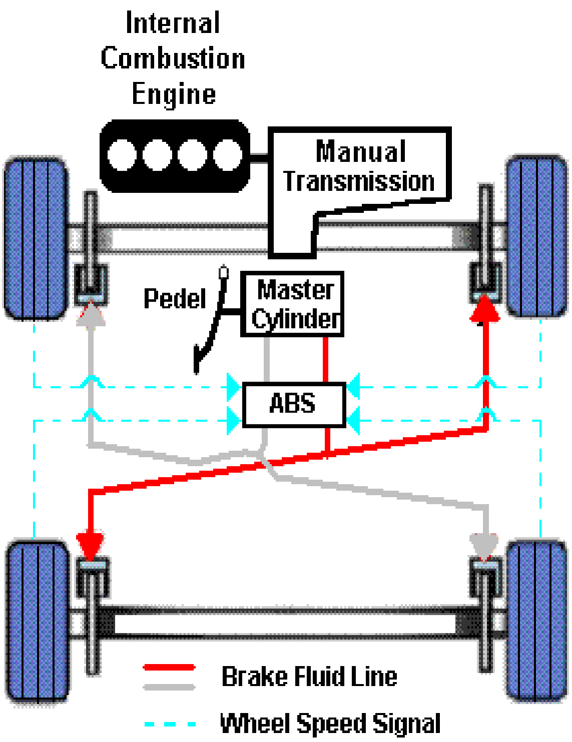

Fig. 1 Layout of the ICE vehicle and braking system

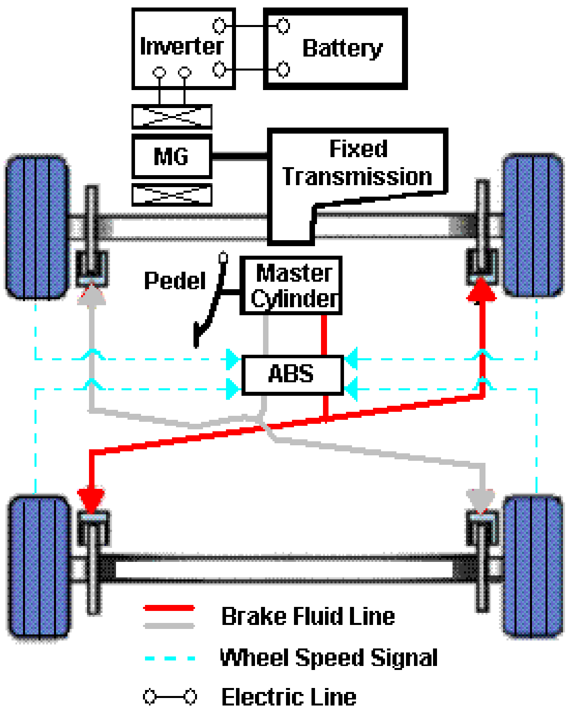

Fig. 2 Layout of the EV and braking system

2.2 Modified braking system with emulated ABS signal

The objective of this system is to allow regenerative system can obtain as much energy as possible by reducing friction brake force be equal to a quantity of regenerative brake force. The layout of modified braking system with emulated ABS signal is shown in Figure 3. The modification is to trap front wheel speed signal to regenerative control unit (RCU) and then send emulated wheel speed signal to ABS control unit to simulate the wheel locking-up situation. Consequently, ABS control unit will automatically reduce brake fluid pressure at front wheel. On one hand, if sum of regenerative and front friction brake force is more than force of front wheel requirement, emulated signal is sent to reduce friction brake force. On the other hand, if friction brake force is not enough, the RCU will suddenly stop sending emulated signal to allow ABS to increase proper friction brake force. The designed algorithm of RCU can be described as followed as to distribute friction brake and regenerative brake force by using signal of motor RPM, brake fluid pressure at Master cylinder (Pm) and Caliper (Pc) and Battery SOC.

2.3 Modified braking system with brake fluid distribution in master cylinder

Mechanism of this system is to control solenoid valve to close brake fluid pressure by using solenoid valve at the outlet of master cylinder while a required brake force of four wheels is lower than the available regenerative brake force. The layout of this system is shown in figure 4. The 4 wheel brake force can be computed from outlet pressure of mater cylinder. Motor RPM and %SOC can be used to calculate the regenerative brake force.

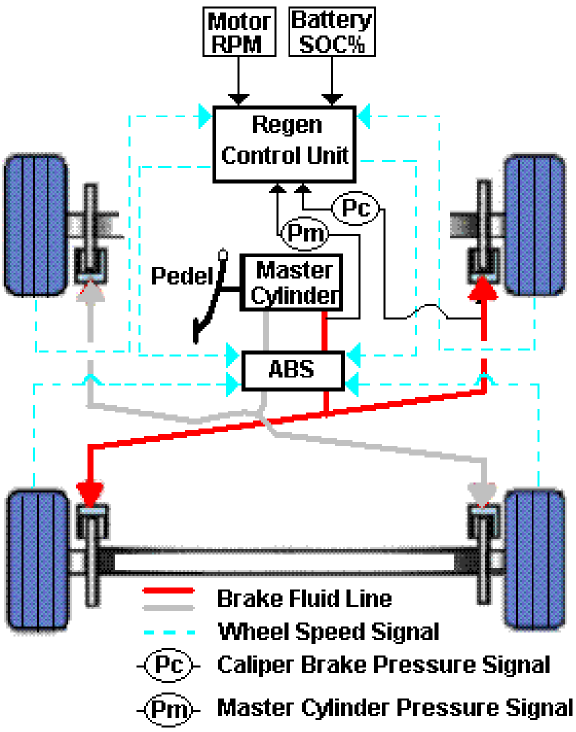

Fig. 3 Layout of regenerative system of modified braking system with emulated ABS signal

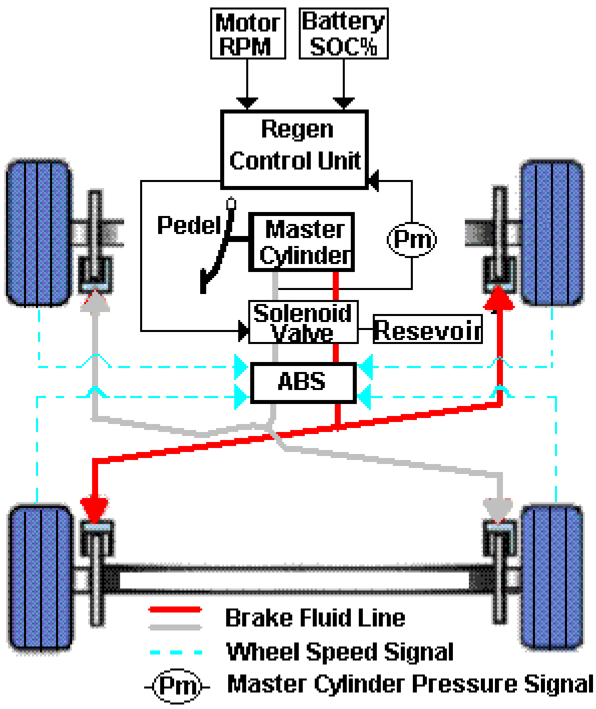

Fig. 4 Layout of regenerative system of modified braking system with brake fluid distribution in master cylinder

3. Regenerative Braking Algorithm

To manage brake force during using regenerative brake, the first thing must be achieved is to calculate magnitude of regenerative brake torque at the front wheel. This torque depends on the motor-generator torque characteristic at given RPM (T_{Reg_Motor}), gear ratio (i), and differential gear ratio (N_d). The Regenerative brake torque at front wheel (T_{Reg_FW}) can be represented as

$$T_{Reg\_FW} = T_{Reg\_Motor} \cdot i \cdot N_d \qquad (1)$$

In order to easily measure and compare brake force, T_{Reg_FW} is converted to be equivalent regenerative brake pressure (ΔP) since all sensors used to measure brake force at each point are pressure sensors and in algorithm, brake force is compared by using pressure. ΔP is equal to hydraulic pressure at front caliper that should be reduced while regenerative and friction brake collaborate.

$$\Delta P = \frac{T_{Reg\_FW}}{A_{wcf} \times \mu \times 2 \times r} \qquad [9] \qquad (2)$$

Where A_{wcf} is the cylinder area of front caliper, μ is the friction coefficient, and r is the effective radius of brake disk.

The strategy to control regenerative system of modified braking system with emulated ABS signal is shown in figure 5. The brake assist (BA) is a mode automatically increasing hydraulic brake pressure when the pedal is suddenly pressed. If BA operates meaning that this braking is in panic situation, the brake pressure should not be reduced by all means. When the braking is not on BA mode, the RCU calculates ΔP by using equation (2) and then multiply by Weight Factor, function of battery SOC, shown in Figure 6. In this study, weight factor equals to one at SOC range of 0-80% to increase battery SOC level but at range of 80-100%, weight factor linearly decline to protect battery damage of overcharging. If ΔP^*, referred to available regenerative brake force, is larger than $P_m - P_c$, RCU sends emulated signal to ABS control unit making ABS automatically reduces friction brake force (P_c). Where P_m is master cylinder pressure referred to required brake force, P_c is caliper pressure referred to friction brake force. If ΔP^* is smaller than the difference of P_m and P_c, RCU stops sending emulated signal to increase brake friction brake force .

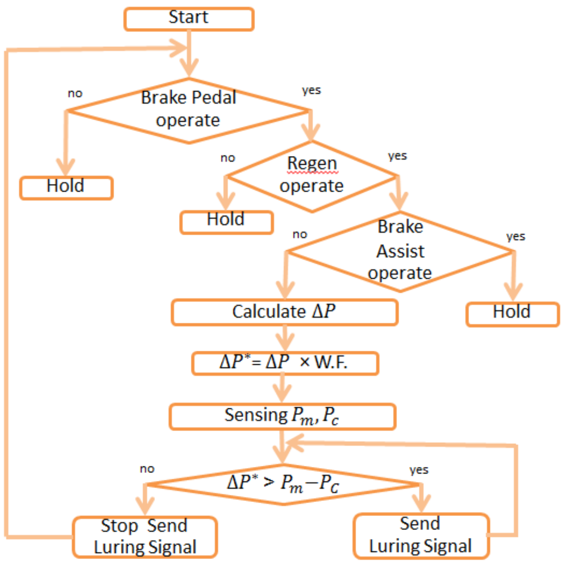

Fig. 5 Strategy flow chart of regenerative system of modified braking system with emulated ABS signal

In Figure 7, the strategy for regenerative system modified braking system with brake fluid distribution in master cylinder is presented. Most of it is same to the first strategy but the difference is that $\Delta P^*$and only P_m is compared to drive solenoid valve to control hydraulic brake pressure. P_m is sum total of both hydraulic pressures at master cylinder outlet. If ΔP^* is more than P_m, RCU drives solenoid to cut brake pressure. On the other hand, RCU stops driving solenoid to open hydraulic pressure normally.

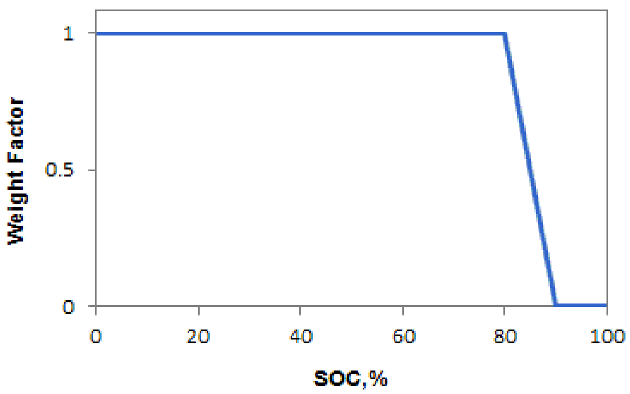

Fig. 6 Weight Factor vs. Battery SOC%

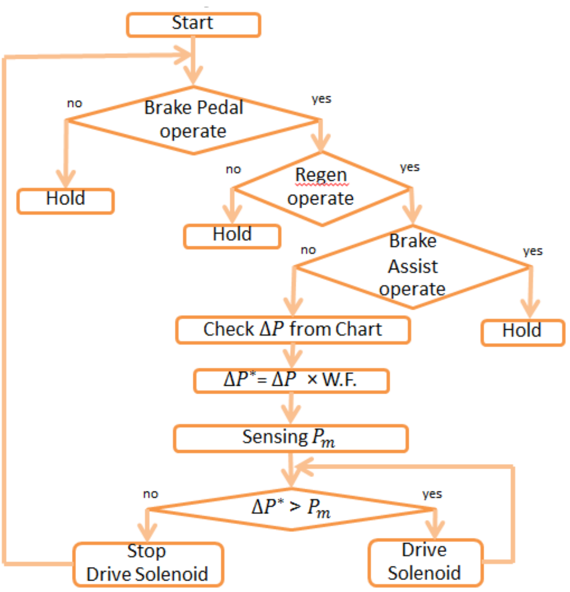

Fig. 7 Strategy flow chart of regenerative system of modified braking system with brake fluid distribution in master cylinder

4. Simulation Model

Four models are implemented by using MATLAB Simulink software and use same parameters shown in Table. 1. All models consist of model of conventional braking system with ABS and regenerative system of non-modified braking system, modified braking system with emulated ABS signal, and modified braking system with brake fluid distribution in master cylinder. The model of conventional brake with ABS is made to compare braking distance and braking pressure contour with all model of regenerative.

Table 1 Total parameter of vehicle

Motor	
Peak torque	240 Nm
Peak Power	75 kW
Transmission system	
Fixed gear ratio (i)	1.303
Rear axle gear ratio (Nd)	4.294
Vehicle	
Vehicle mass (m)	1520 kg
Frontal area (dA)	2.146 m^2
Drag coefficient (Cd)	0.35
Tire radius (Rt)	0.32 m

Simulation flowchart is shown in figure 8 in which each box is represented as component of calculation. The initial value of this simulation is brake demand and vehicle speed. Started from brake demand, brake pressure signal in hydraulic pressure box is controlled by ABS control unit box from which the result is friction brake torque. In case of regenerative operation, the controlling signal of regenerative box is send to control friction brake force. Vehicle speed can be used to calculate stopping distance of vehicle and wheel speed can be used to calculate motor torque available by using motor-torque look-up table. The vehicle and wheel speed are also used to calculate slip rate to send to ABS control unit and find friction coefficient (Mu) between road and tire surface at Mu-slip look-up table. The friction coefficient is used to calculate vehicle speed and inertia torque of vehicle. Regenerative energy is computed from wheel RPM and generator torque in Regenerative energy box.

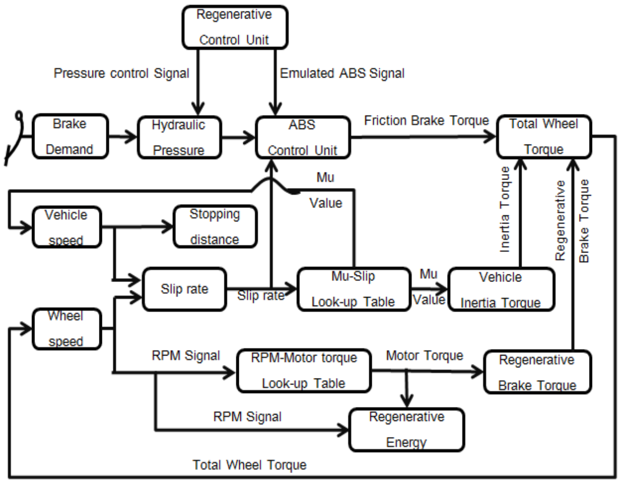

Fig. 8 Simulation Model

5. Simulation result and discussion

The percentage of braking distance is shown in Fig. 9 comparing that braking distance of conventional brake with ABS is equal to 100%. By the result, all regenerative system can reduce brake distance since they have additional brake force from regenerative braking. The lowest braking distance is of regenerative system of non-modified braking system because no strategy is used to reduce friction brake force while regenerative brake force works together. The medium braking distance is of regenerative system of modified braking system with brake fluid distribution in master cylinder since it cut brake pressure during only starting point. The greatest braking distance of three regenerative systems and nearest to conventional braking distance is of regenerative system of modified braking system with emulated ABS signal because it have the strategy to decrease friction brake force corresponding to regenerative brake force all the operation time.

Fig. 10 shows front wheel brake pressure contour of four models. The green line is brake pressure at master cylinder or demanded brake force and the blue line is brake pressure at front brake caliper. Fig. 10(a) is brake pressure of conventional brake with ABS. The brake pressure of master cylinder is equal to brake-caliper pressure meaning that ABS still has not operated. Figure 10(b) shows brake-pressure contour of regenerative system of non-modified braking system. Since, this system, front wheel have two brake forces working together but it has not used any strategy to lessen friction brake force making front wheel locking. Hence, ABS has operated to diminish friction brake force showing of blue line. Figure 10(c) is brake pressure outline of regenerative system of modified braking system with emulated ABS signal. The pressure friction brake is lower than required brake pressure corresponding to regenerative brake force owning to its strategy. Figure 10(d) provides brake pressure of regenerative system of modified braking system with brake fluid distribution in master cylinder. The strategy outcome of this system is only the period of 0-1.2 second that caliper brake pressure is equal to zero because of cutting hydraulic pressure by solenoid valve. However, the result of pressure reduction at the second of 2.8-4.3 is of ABS operation.

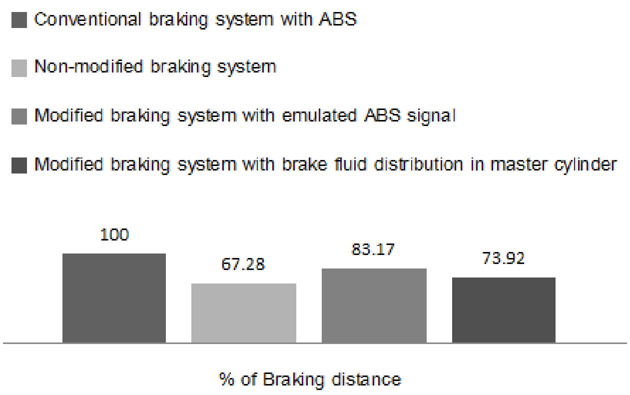

Fig. 9 Percentage of Braking distance

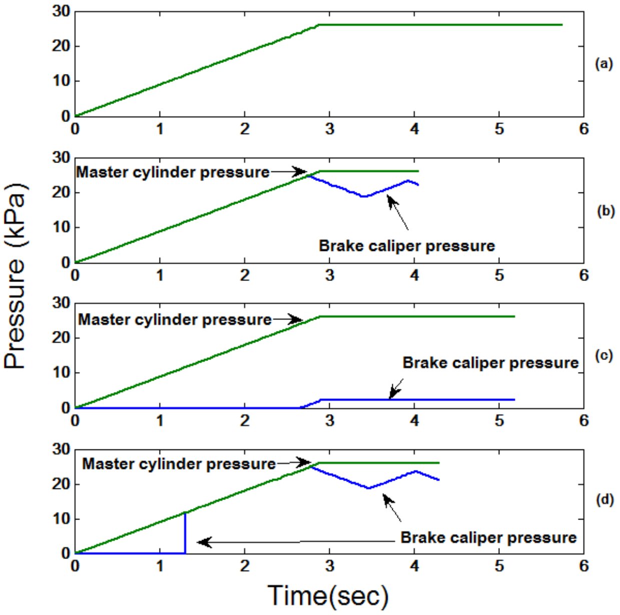

Fig. 10 Brake pressure contour

a) Conventional braking system with ABS
b) Non-modified braking system
c) Modified braking system with emulated ABS signal
d) Modified braking system with brake fluid distribution in master cylinder

Regenerative energy of each system is different depending on controlling the friction brake force, pressure at front brake caliper. The regenerative system of modified braking system with emulated ABS signal so work properly that it is the first one that can provide energy the most of any regenerative system in this study. The energy gave by regenerative system of modified braking system with brake fluid distribution in master cylinder is second order since it have pressure controlling only in starting time. The lowest provided energy is of regenerative system of non-modified braking system because of no friction brake reduction strategy.

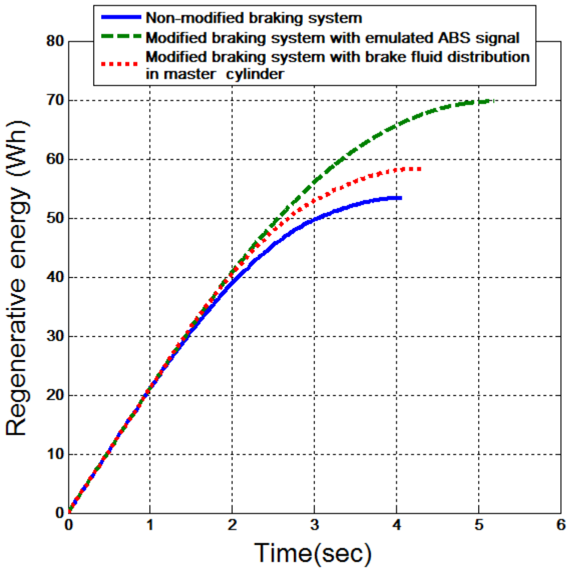

Fig. 10 Regenerative energy of each system

6. Conclusion

In this study, three candidates of regenerative braking strategies are examined by using MATLAB Simulink software. The braking situations are simulated to test design criteria of braking performance focused on braking distance and regenerative energy. The regenerative strategy of modified braking system with emulated ABS signal is the most proper in this study. Nevertheless, these criteria results must be validated in next phrase and also to investigate other criteria such as cost and feasibility.

7. References

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