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An Introduction to Regenerative Braking of Electric Vehicles as Anti-Lock Braking System

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***Abstract*— Anti-lock braking systems (ABS) are well known in the automotive industry as one of the most critical active safety systems. ABS improves vehicle safety by reducing longitudinal breaking distance. This occurs by the control of the wheel slip. In this study, a basic modeling approach has been introduced on a quarter car model by using ANSOFT Simplorer for the following braking modes: hydraulic braking and all electric vehicle regenerative braking concept.**

I. Introduction

Electric or hybrid electric vehicles propose not only better fuel economy and less environmental pollution but also superior performance of braking, traction control and stability control systems employing motoring and regenerative braking capability of electric machines.

A car braking system is one of the major factors for the driving safety. The introduction of the Anti-Lock Braking Systems has contributed to improve the security of modem cars decisively by automatically controlling the brake force during braking in potentially dangerous conditions such as braking on iced or wet asphalt, panic braking, etc. [1]

This paper starts with development of quarter car model (QCM). First a hydraulic ABS model is applied to the QCM. Later, modification of permanent magnet (pm) brushed dc machine equations for the simulation of field weakening region characteristics of PM brushless dc machine is introduced. Finally this model is applied to QCM to investigate regenerative braking performance of electric vehicles by means of ABS.

II. Quarter Car Model

Forces acting on a vehicle is shown in Fig. 1, which are rolling resistance (F_w), aerodynamic drag force (F_a), slope friction force (F_s) and force due to vehicle inertia (F_{acc}). F_x denotes the tire braking force.

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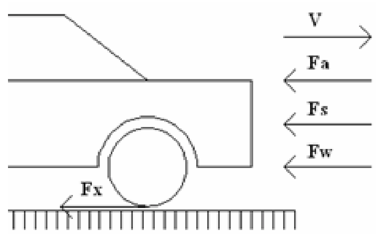

Fig. 1. Forces acting on the vehicle.

Forces acting on one wheel of a vehicle;

$$F_w = c_t.m.g.\cos\alpha \quad (1)$$

$$F_s = m.g.\sin\alpha \quad (2)$$

$$F_a = 0.5.c_r.\delta.A_f.V^2 \quad (3)$$

$$F_{acc} = m.\frac{dV}{dt} \quad (4)$$

where c_t, m, α, c_r, δ, A_f and V are wheel rolling resistance coefficient, quarter vehicle mass (kg), slope angle (rad), aerodynamic coefficient, air density (kg/m^3), vehicle frontal area and vehicle speed (m/s) respectively. The rest of the paper omits slope angle considering only straight road driving.

Longitudinal vehicle dynamics of quarter car during braking can be given as;

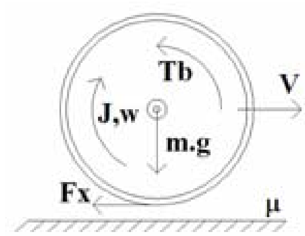

Fig. 2. Wheel longitudinal dynamics

$$-F_x - F_w - F_s - F_a = m.\frac{dV}{dt} \quad (5)$$

$$F_x = \mu.m.g \quad (6)$$

F_x is tire braking force and μ can be calculated based on a Pacejka magic tire formula [2] or taken from a table of μ vs. slip ratio (s). Slip ratio is defined as;

$$s = \frac{w_v - w_w}{max(w_v, w_w)} \tag{7}$$

where w_v and w_w represents vehicle and wheel angular speeds respectively.

For this study μ is calculated based upon the graph in Fig. 3, which represents a dry road condition.

Tire model can be given as;

$$F_x.r\text{-}T_b \;=\; J.\frac{d\omega}{dt} \tag{8}$$

where r, T_b, J and w are wheel radius, braking torque, wheel inertia and wheel angular velocity respectively (Fig. 2).

TABLE 1
VEHICLE PARAMETERS USED IN MODEL

Symbol	Quantity	Value
m	Quarter car mass	425 kg
r	Wheel radius	0.325 m
A_f	Vehicle frontal area	3.1 m^2
c_r	Tire rolling resistance coefficient	0.3
c_t	Aerodynamic resistance coefficient	0.01
J	Wheel inertia	0.5 $kg.m^2$

Finally, quarter car model during braking is represented in the following Fig. 4. For this model, definition of initial speed is crucial. Initial speed is selected as 100 km/h for both vehicle and wheel for all of the simulations.

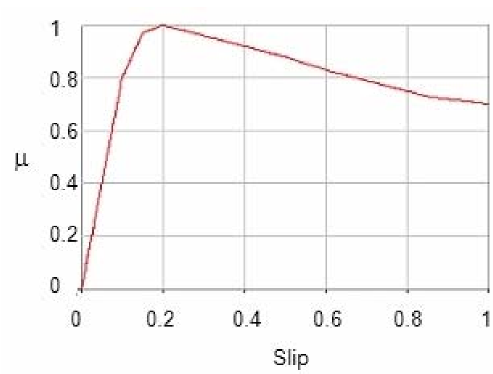

Fig. 1. μ - slip curve used for tire modeling

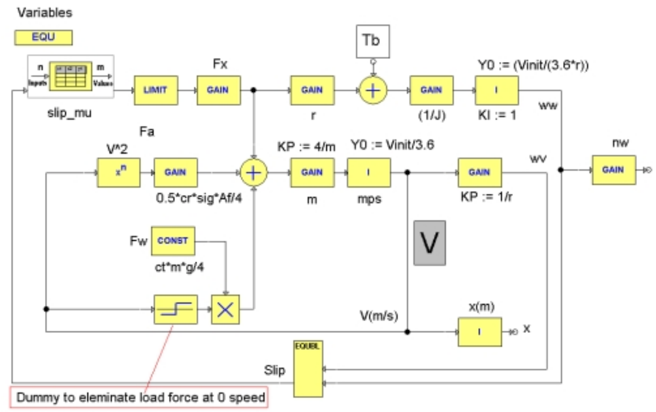

Fig. 4. Quarter car model during braking

III. HYDRAULIC ABS BRAKING

The purpose of ABS is to optimize the braking effectiveness and maintain vehicle stability under various road conditions. It is achieved by controlling the slip ratio at the point where maximum braking force can be applied to the wheels.

For the control of the ABS, optimum slip ratio is entered to the controller as reference value. Slip error then is fed to hydraulic actuator.

The dynamic model of hydraulic fluid lag of braking system is used as the following first order transfer function:

$$G(s) = \frac{k}{\tau.s + 1} \tag{9}$$

where for this study k and τ are selected as 100 and 0.01 respectively.

Then braking torque is simply achieved by integrating the hydraulic fluid and multiplying by a constant as show in Fig. 5.

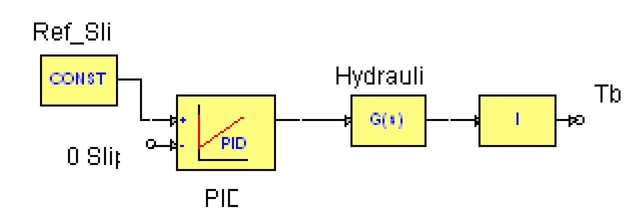

Fig. 5. Hydraulic ABS model

Integration of the hydraulic ABS model and QCM is given in Fig. 6.

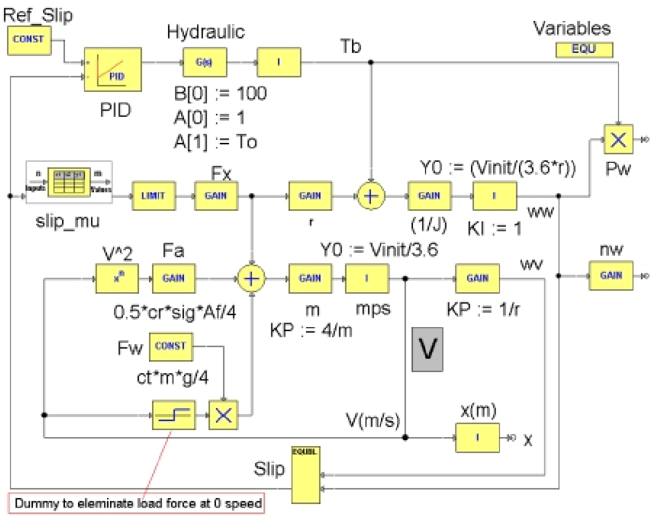

Fig. 6. Integration of hydraulic ABS to QCM

During braking simulation, maximum braking torque of the system is limited to 1500 Nm. Reference slip value is entered as 0.2 seeing that maximum braking force occurs at this point as shown in Fig. 3.

In Fig. 7, vehicle and wheel speeds (km/h) are plotted during simulation. Total braking time is 3.5 s. Around 1.5 s, wheel slip ratio reaches 0.2 where maximum braking force is achieved. Total distance traveled during braking is 57.27 m.

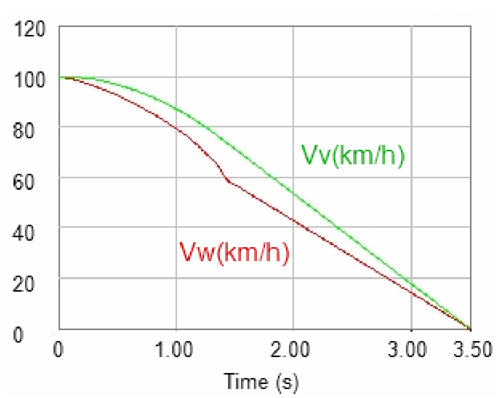

Fig. 7. Vehicle (Vv) and wheel (Vw) speeds vs. time simulation result for hydraulic braking.

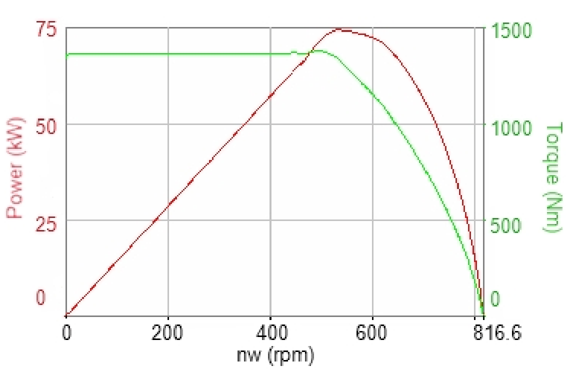

Fig. 8. Braking power and torque vs. wheel rotational speed (nw)

Braking power and torque vs. wheel rotational speed is plotted in Fig. 8. As can be seen from the figure nominal power is 75 kW at 530 rpm and nominal applied braking torque is around 1400 Nm.

IV. Modification of PM Brushed DC Machine Model for Field Weakening Region

Electric vehicle applications require high constant power to constant torque ratio, typically in the range of 3 to 5 for better performance at lower power consumption [3].

For simplification of the overall electric traction system modeling, a dc motor model will be used looking from system engineering point of view.

Conventional permanent magnet stator dc machine model simplified equations can be modified as below to simulate the constant power region of field oriented controlled ac machines;

$$V_a = E_a + R_i.I_a + L_i.\frac{di_a}{dt} \tag{9}$$

$$E_a = k_e(w_r).w_r \tag{10}$$

$$T_e = k_t(w_r).I_a \tag{11}$$

where V_a, E_a, R_i, L_i, k_e, k_t and ω_r represent supply voltage, back EMF voltage, winding resistance, winding inductance, back EMF constant, torque constant and rotor speed respectively.

Considering electromechanical power equality;

$$T_e.w_r = E_a.I_a \tag{12}$$

$$k_t(w_r).I_a = k_e(w_r).w_r \tag{13}$$

$$k_t(w_r) = k_e(w_r) \tag{14}$$

In this modified version of the model, rotor flux value is calculated by an equation block. Until the base speed of the motor, ke is kept constant, above base speed it is decreased proportional to angular rotor speed such that overall back EMF stays at the same value. Above maximum speed, motor is considered as it is in the natural mode and ke is decreased proportional to square of rotor angular speed.

To control the output torque of the electric motor, a current feedback loop is used. PI controller output is amplified by a gain block, which controls voltage source.

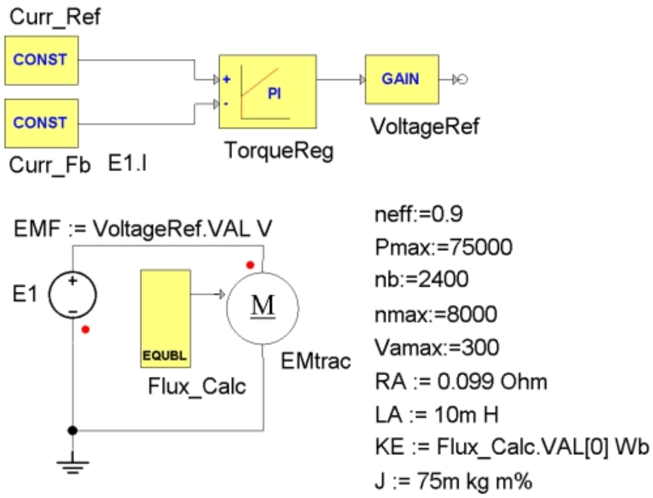

Fig. 9. Modified dc motor and torque loop model

Resultant torque vs. speed graph of the electric motor and corresponding rotor back EMF curve have been given in the following Fig. 10 and Fig. 11.

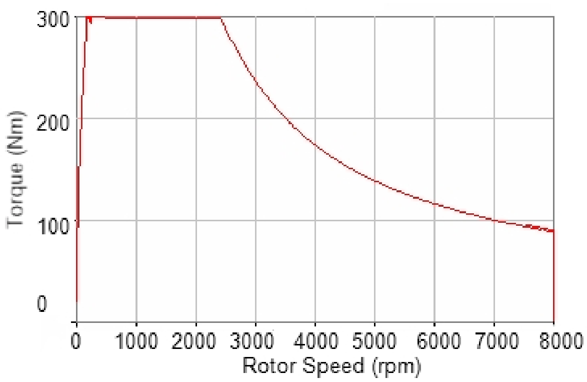

Fig. 10. Torque vs. speed graph

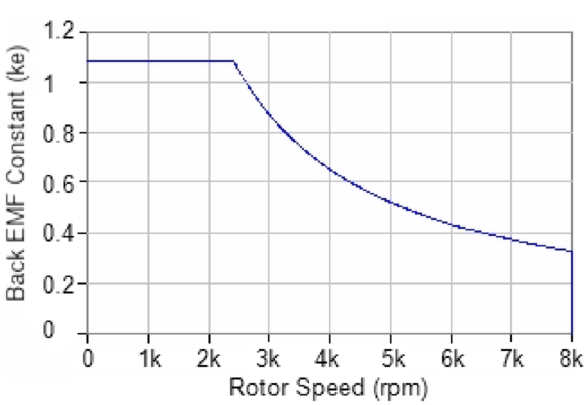

Fig. 11. Rotor Back EMF constant calculated in Flux_Calc Block shown in Fig. 9

V. Regenerative ABS Braking

For the simulation of regenerative abs braking, an electric motor connected to a wheel by a reduction gear is applied to QCM. The ratings of the electric motor are selected as seen in Fig. 9. This motor can supply 300 Nm torque at its shaft. A 5:1 reduction gear is considered to match 1500 Nm torque of hydraulic braking.

The QCM is modified such that total load force is reduced to the motor shaft. So the load torque is reduced by a factor of 5. In the same manner, EM rotor speed is amplified by 5 to reach to the wheel speed. Tire inertia is accepted to be referred to the rotor. Modified version of QCM is given in Fig. 12.

Some of the simulation results are given in Fig.13 and Fig.14. Stopping time is 3 seconds and total traveled distance is 43.95 meters.

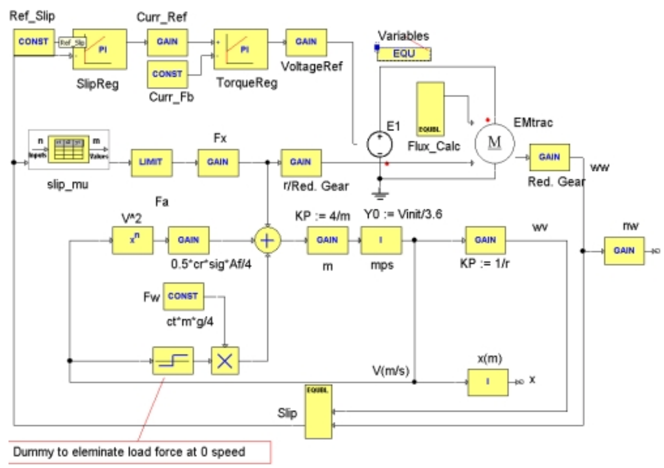

Fig. 12. QCM modified for regenerative ABS braking

In this case, 20% wheel slip ratio has been achieved at the first second. Reaching maximum braking force faster yielded in reduced braking time and distance compared to hydraulic model.

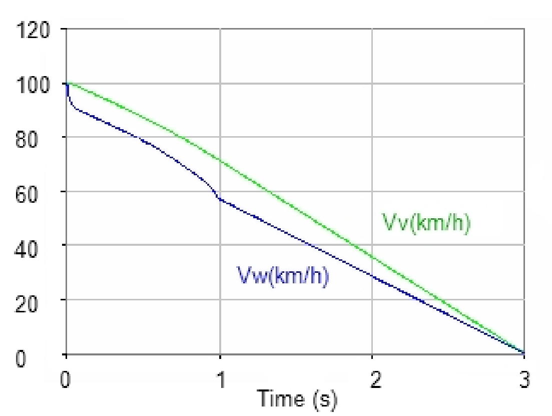

Fig. 13. Vehicle (Vv) and wheel (Vw) speeds vs. time simulation result for regenerative braking.

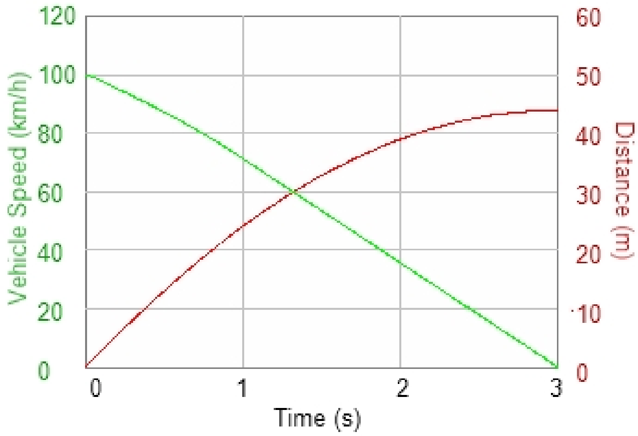

Fig. 14. Stopping distance

VI. CONCLUSION

In this study, basic modeling effort on ABS braking has been given considering hydraulic and all electric approaches on quarter car model. For all electric ABS application, a conventional dc motor model has been modified for field weakening operation.

Simulation results show that regenerative ABS response is better for panic stop situation. By analyzing reliability, cost and sizing issues of electric drives and required energy storage device for regenerative ABS, an improved hybrid ABS solution may be achieved for electrified powertrain applications.

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