International Journal of Technology (2015) 1: 44-52
ISSN 2086-9614 © IJTech 2015

NEW CONTROL SCHEME FOR COMBINED REGENERATIVE AND MECHANICAL BRAKES IN ELECTRIC VEHICLES

Feri Yusivar[1*], Hade Saputra Haslim[1], Yasil Farabi[2], Kusnan Nuryadi[2]

[1]*Department of Electrical Engineering, Faculty of Engineering, Universitas Indonesia, Kampus UI Depok, 16424, Indonesia*
[2]*PT. Melu Bangun Wiweka, Jalan Simpang Tiga Setu No.39, Tambun – Bekasi 17510, Wes Java, Indonesia*

(Received: September 2014 / Revised: January 2015 / Accepted: January 2015)

ABSTRACT

Braking conditions could generate energy that can be reused again for energy conservation. The purpose of regenerative braking in electric vehicles is to use the excess energy from the braking system and convert it to electricity and then store it for further utilization. But when the back current is too high it can cause overvoltage which can result in broken electrical components. Therefore, a voltage limiter is required to limit the q-axis stator current which keeps DC link voltage at a certain value. However, this voltage limiter causes a decrease in the braking torque and actual speed that does not follow the reference speed. To overcome this problem, the mechanical brake should be combined with a regenerative brake in electric vehicles, so the vehicle speed can always follow the reference speed. A new control scheme for combining a regenerative braking system with mechanical braking system to overcome the overvoltage problem in electric vehicle is proposed in this paper. Using a combination between regenerative and mechanical braking, the actual speed could follow the reference speed even when voltage limiter is active. The effectiveness of the control scheme is validated through simulation. Actual speed could follow the speed reference with delays in about 1.5s–2.5s and by varying gain in IP controller, the delay could be reduced to become about 1 second, so the braking will be more accurate.

Keywords: DC link; Electric vehicle; Induction motor; Mechanical braking; Regenerative braking

1. INTRODUCTION

Most electric vehicles have a regenerative braking system. During braking, the motor acts as generator and converts the energy originating from the movement of the vehicle back into electricity and then it is saved in a battery or another storage system for further reuse. Some problems occur while attempting to address the energy saving issues in the electrical drive system. In one case, the motor is operated at high-speed. A high-speed motor operation capability can provide high kinetic energy to be recovered by the regenerative control system. This high-speed operation is limited by the output voltage of the inverter.

Electric vehicles usually use a regenerative braking control system for energy conservation and for lower maintenance purposes (Anne, 2010). Under braking conditions, overpowered kinetic energy will occur and be stored as electric energy, so that it can be used for another purposes

[*] Corresponding author's email: yusivar@ee.ui.ac.id, Tel. +62-21-7270078, Fax. +62-21-7270077
Permalink/DOI: http://dx.doi.org/10.14716/ijtech.v6i1.780

(Hasegawa, 1999). But there is a back current that causes the DC link voltage of the inverter to rise. The regenerative braking will be interrupted by an over voltage protection mechanism when the filter capacitor voltage *vf* exceeds its permitted value. Over voltage protection does not create optimal operating conditions for the braking system. In order to obtain the desired braking power, regenerative braking needs to be combined with mechanical braking. Mechanical braking only works when the regenerative braking does not yield the desired braking power or when the over voltage protection is active. A combination between regenerative and mechanical braking will be the best solution to obtain optimum braking torque.

2. METHODOLOGY

In this paper a control scheme for combining a regenerative braking system with a mechanical braking system to overcome the overvoltage problem in electric vehicles is proposed. The proposed control scheme is validated by simulating the whole system in detail. The induction motor, DC link circuit model, rotor flux oriented control, voltage controller, and the proposed braking method are described in the following section.

2.1. Induction Motor and DC Link Circuit Modeling

The induction motor that used is a three phase-squirrel cage induction motor. The motor model should be transformed from a three-phase into a two-phase motor model using the transformation proposed by Clarke and Park. The induction motor control uses a rotor flux oriented control (RFOC) scheme (Yusivar, 2000).

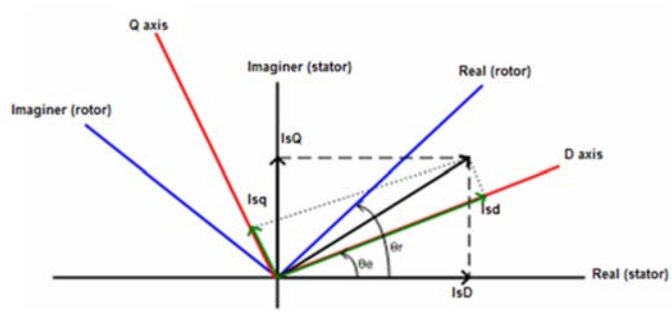


Figure 1 Rotor flux reference frame

The induction motor model is expressed in the following equations (Vas, 1992).

$$\frac{d}{dt}i_{sd} = \frac{1}{L_s\sigma}v_{sd} + \left(-\frac{R_s}{L_s\sigma} - \frac{(1-\sigma)R_r}{L_r\sigma}\right)i_{sd} + \omega_e i_{sq} + \frac{(1-\sigma)R_r}{L_r\sigma}i_{mrd} + \frac{(1-\sigma)p\omega_r}{\sigma}i_{mrq} \quad (1)$$

$$\frac{d}{dt}i_{sq} = \frac{1}{L_s\sigma}v_{sd} - \omega_e i_{sd} + \left(-\frac{R_s}{L_s\sigma} - \frac{(1-\sigma)R_r}{L_r\sigma}\right)i_{sq} + \frac{(1-\sigma)R_r}{L_r\sigma}i_{mrq} - \frac{(1-\sigma)p\omega_r}{\sigma}i_{mrd} \quad (2)$$

$$\frac{d}{dt}i_{mrd} = -\frac{R_r}{L_r}i_{mrd} + \frac{R_r}{L_r}i_{sd} + (\omega_e - p\omega_r)i_{mrq} \quad (3)$$

$$\frac{d}{dt}i_{mrq} = -\frac{R_r}{L_r}i_{mrq} + \frac{R_r}{L_r}i_{sq} + (\omega_e - p\omega_r)i_{mrd} \quad (4)$$

$$\frac{d}{dt}\omega_r = \frac{\left(p\frac{L_m{}^2}{L_r}(i_{sq}i_{mrd} - i_{sd}i_{mrq}) - T_L - B\omega_r\right)}{J+I} \quad (5)$$

The DC Link circuit is modeled as shown in Figure 2 (Yusivar, 2000).

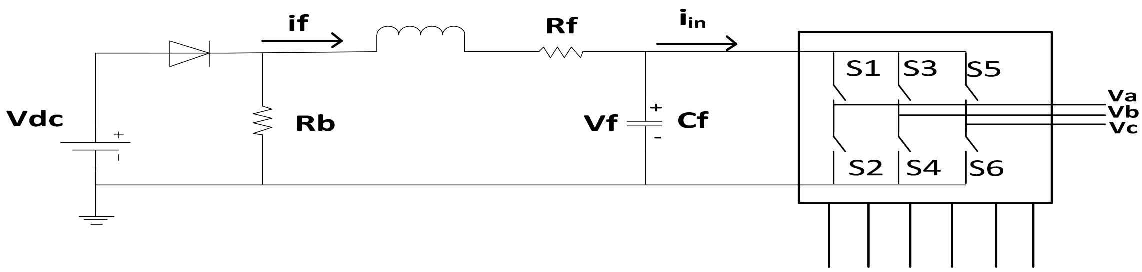


Figure 2 DC link circuit

The DC Link model consists of two conditions: motoring condition and braking condition. In the motoring condition, the diode is on and the DC Link model is expressed in Equations (6) and (7). In the braking condition, the diode is off and the DC Link model is expressed as Equations (8) and (9).

$$\frac{dv_f}{dt} = \frac{1}{C_f}(i_f - i_{in}) \tag{6}$$

$$\frac{di_f}{dt} = \frac{-v_f + v_{dc} - R_f i_f}{L_f} \tag{7}$$

$$\frac{dv_f}{dt} = \frac{1}{C_f}(i_f - i_{in}) \tag{8}$$

$$\frac{di_f}{dt} = \frac{-(R_f + R_b)i_f - v_f}{L_f} \tag{9}$$

2.2. Rotor Flux Oriented Control (RFOC) and Voltage Controller

The motor drive braking system is modeled as shown in Figure 3. The braking system consists of regenerative braking and mechanical braking. Mechanical braking directly gives braking torque to the induction motor, while regenerative braking is provided by controlling the q-axis current stator.

The system control is divided into three components, which are speed control, RFOC, and the proposed braking method. There is also a speed profile to keep the speed input as desired. This will limit the input speed acceleration and deceleration before it is fed into the speed controller.

The speed controller is an Integral Proportional (IP) controller that is expressed in Equation (10). The IP controller is used since it provides a better performance than the PI controller (Yusivar, 2000). Voltage controller uses a proportional integral (PI) controller to maintain the voltage in order to avoid overvoltage in the inverter. The voltage controller limits the q-axis current stator, which also limits the output of the IP controller. The output of the speed controller, after being limited by voltage controller, is regulated. When it reaches the limitation level defined by the integration initial value of next iteration, then it is reset to the integration initial value of previous iteration to prevent a windup phenomenon (Yusivar, 2001).

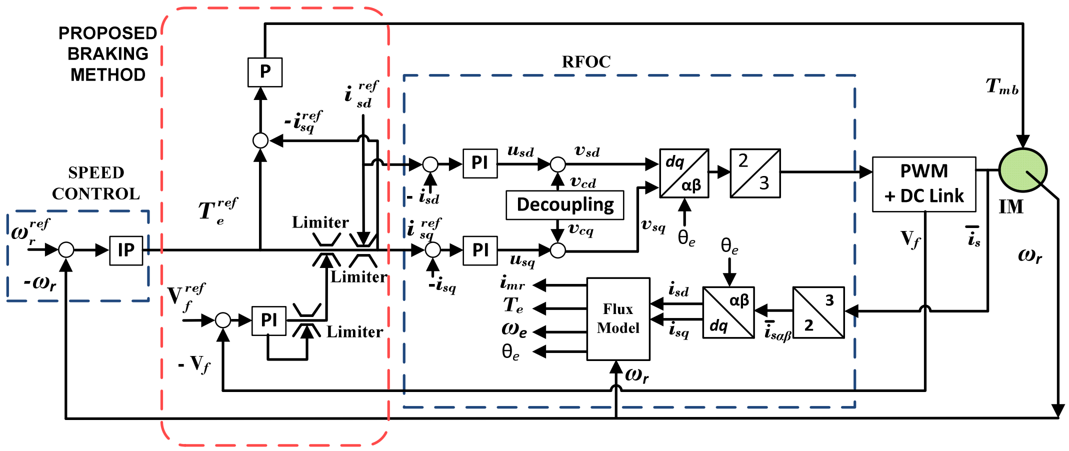


Figure 3 Electric vehicle braking control system

$$Te^* = K_{spi}\int(\omega_r^* - \omega_r)dt - k_{spp}\omega_r \tag{10}$$

The induction motor is controlled by using the Rotor Flux Oriented Control (RFOC). Decoupling is used to minimize interaction and the nonlinear part of motor which is showed in the equations below.

$$v_{sd} = R_s i_{sd} + \sigma L_s \frac{d}{dt} i_{sd} - \omega_e L_s \sigma i_{sq} + L_s(1-\sigma)\frac{d}{dt} i_{imr} \tag{11}$$

$$v_{sq} = R_s i_{sq} + \sigma L_s \frac{d}{dt} i_{sq} + \omega_e L_s \sigma i_{sd} + L_s(1-\sigma)\omega_e i_{imr} \tag{12}$$

The decoupling voltages and voltage references are expressed in the following equations.

$$\boldsymbol{v_{cd} = -\left(\frac{R_r i_{sq}}{L_r i_{mr}} + p\omega_r\right) L_s \sigma i_{sq} + L_s(1-\sigma)\frac{d}{dt} i_{mr}} \tag{13}$$

$$\boldsymbol{v_{cq} = \left(\frac{R_r i_{sq}}{L_r i_{mr}} + p\omega_r\right) L_s \sigma i_{sd} + \left(\frac{R_r i_{sq}}{L_r i_{mr}} + p\omega_r\right) L_s(1-\sigma) i_{mr}} \tag{14}$$

The current controller is a Proportional Integral (PI) controller, in which d-axis and q-axis current controller in domain s is expressed in Equations (15) and (16) respectively.

$$\boldsymbol{u_{sd} = k_{idp}(i_{sd}^* - i_{sd}) + \frac{k_{idi}}{s}(i_{sd}^* - i_{sd})} \tag{15}$$

$$\boldsymbol{u_{sq} = k_{iqp}(i_{sq}^* - i_{sq}) + \frac{k_{iqi}}{s}(i_{sq}^* - i_{sq})} \tag{16}$$

During braking conditions the DC Link diode is off. Since the value of resistor (Rb) is very large, then the current charges the capacitor (Cf). If the current is increased over the limit of capacitor, it will cause overvoltage and this could damage the inverter component. For this reason, there is a need to design a controller using a PI (Proportional Integral) controller to limit the stator current on the q axis. The condition of the DC Link voltage controller is expressed in Equation (17).

$$\boldsymbol{u_{vf} = k_{vfp}(v_f^* - v_f) + k_{vfi}\int (v_f^* - v_f)} \tag{17}$$

2.3. Proposed Braking Method

Regenerative braking will be combined with mechanical braking to provide sufficient braking torque. This braking method works when the voltage limiter is active or when the regenerative braking could not provide braking torque properly. The q-axis current stator is limited by the voltage controller during braking conditions; therefore, the torque which is needed for braking is insufficient. Mechanical braking is used to compensate for the braking torque while the voltage limiter is active. Figure 4 shows a block diagram of the proposed control scheme for the combined regenerative and mechanical braking systems; (the whole electric vehicle braking control system is shown in Figure 3).

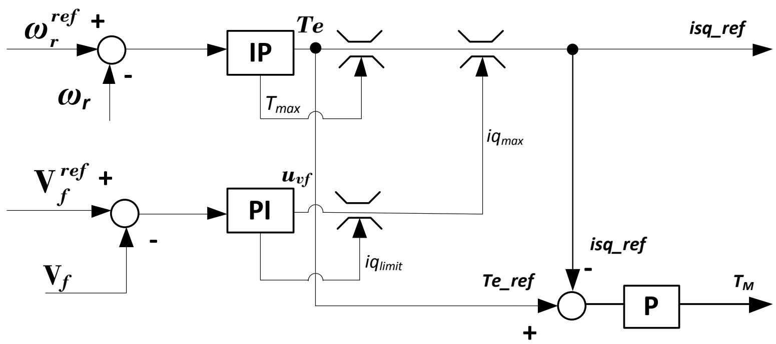


Figure 4 Block diagram of regenerative and mechanical braking

The value of mechanical braking comes from the difference between the current stator q-axis before being limited (i_{sq_ref}) and after being limited by the voltage controller (T_{e_ref}). The proportional (P) gain factor is used to adjust the mechanical braking torque.

$$T_m = P*(T_{e\_ref} - i_{sq\_ref}) \quad (18)$$

However, a time delay occurs on the system which could mean that the braking time is delayed and this could result in a hazardous condition. Using an algorithm to vary the gain of the IP controller could affect the speed of the vehicle. The gain will be added to the gain in the integration part and then multiplied by the speed error. As the gain increases, the acceleration of the monorail will be increased. So, based on the speed profile, when starting from a fixed speed the gain is higher; but when making a transition to another fixed speed the gain becomes lower.

3. RESULTS AND DISCUSSION

In order to validate the effectiveness of the proposed braking control scheme, a simulation is carried out. The simulation is run under SIMULINK in MATLAB with C language programming which is integrated in MATLAB S-function, known as C-Mex S-function.

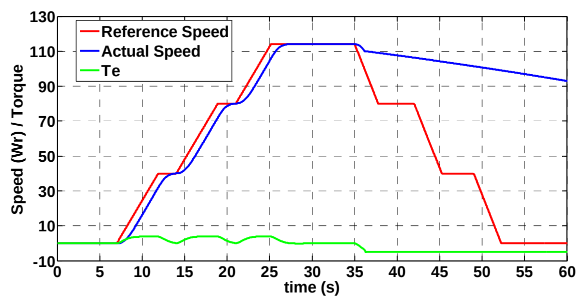
The speed acceleration is limited to 1.2 m/s^2 and the deceleration is limited to -0.6 m/s^2. The DC link capacitor voltage is limited in 400 volts. The model parameters of the induction motor and the DC link circuit are listed in Table 1.

3.1. Regenerative Braking

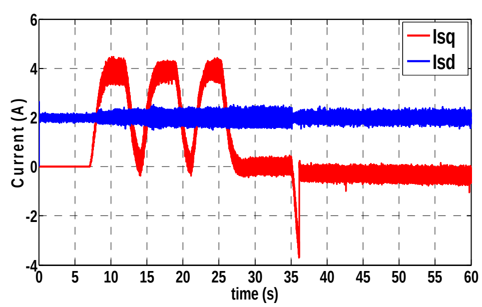
Firstly, the braking system using regenerative braking without mechanical braking is simulated, while the DC link voltage is limited to 400 volts. The results are shown in Figure 5.

Table 1 Induction motor and dc link circuit parameters

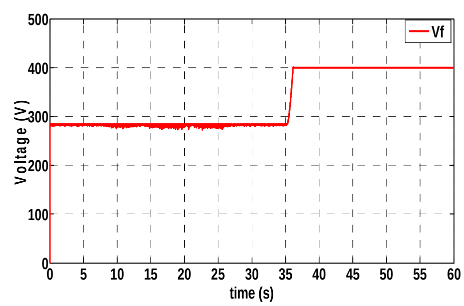
Quantity	Symbol	Value
Motor Capacity	P_m	1 [hp]
Stator resistance	R_s	2.76 [Ω]
Magnetizing inductance	L_m	227.9 [mH]
Rotor resistance	R_r	2.90 [Ω]
Induction motor inertia	J	0.0436 [kg.m^2]
Monorail inertia	I	0.36046 [kg.m^2]
Stator inductance	L_s	234.9 [mH]
Rotor inductance	L_r	234.9 [mH]
Number of poles pair	p	2
Magnetic field	B	0.0005 [Wb]
DC voltage	V_{DC}	283 [V]
Braking resistance	R_b	5000 [Ω]
DC link resistance	R_f	0.115 [Ω]
DC link inductance	L_f	23 [mH]
DC link capacitance	C_f	3.3 [mF]



(a) Speed reference (red), actual speed (blue), and electric torque (green)



(b) Stator current q-axis (red) and stator current d-axis (blue)



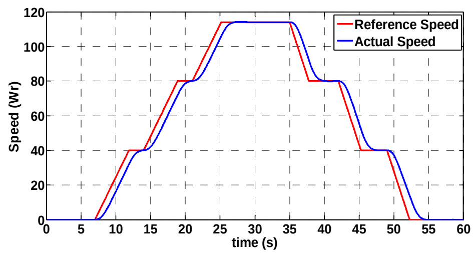
(c) DC link voltage

Figure 5 Regenerative braking with voltage limiter

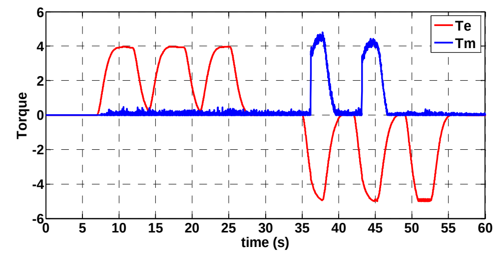
Figure 5(a) shows that during braking conditions, the actual speed does not follow the reference speed. At the same time, the DC link voltage reaches the 400-volt limit as shown in Figure 5(c). The DC link voltage is limited to 400 volts to prevent damage to the inverter components. However, the braking torque will not be sufficient as the vehicle speed could not follow its reference speed. Therefore, an additional braking torque from mechanical brake is needed.

3.2. Combination Regenerative and Mechanical Braking

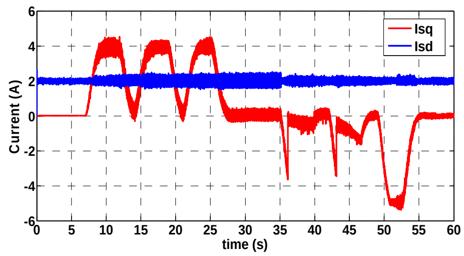
A combination regenerative and mechanical braking is the applied to the system and is simulated. The results are shown in Figure 6.



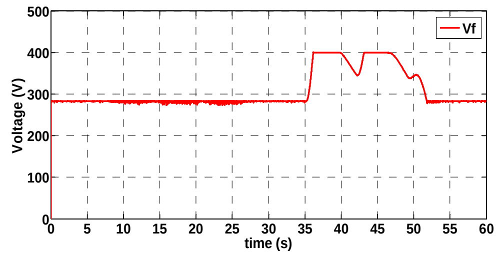
(a) Reference speed (red) and actual speed (blue)



(b) Electric torque (red) and mechanical torque (blue)



(c) Stator current q-axis (red) and stator current d-axis (blue)



(d) DC link voltage

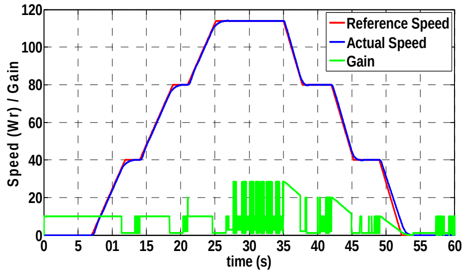
Figure 6 Combined regenerative and mechanical braking

In Figure 6(a), the actual speed could follow the reference speed, even when the voltage limiter is active. Figure 6(b) shows that during braking (when the electric torque Te is negative), the mechanical torque will be active if the DC link voltage reaches its limit of 400 volts and this will compensate for the insufficient electrical torque so the braking torque is optimal. Mechanical braking is activated only when the dc link voltage is limited. As seen in Figures 6(b) and 6(d), at a rate of 36 seconds, the mechanical braking is active and the dc link voltage is limited to 400 volts, but when the voltages drop to below the limit (in t=40 seconds), mechanical braking does not work until the dc link reaches the voltage limit again in t=44 seconds.

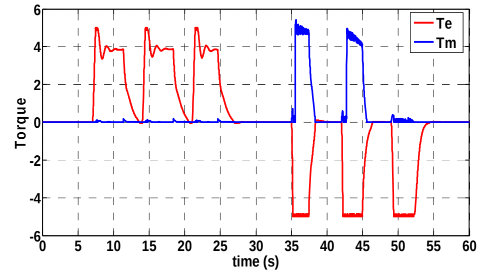
The combination between regenerative and mechanical braking has shown good results that the actual speed could follow the reference speed. However, there is a delay in actual speed of about 1.5s–2.5s as shown in Figure 6(a). To overcome this problem, a gain scheduling scheme is applied to the IP speed controller.

3.3. Combination Regenerative and Mechanical Braking with Gain Scheduling

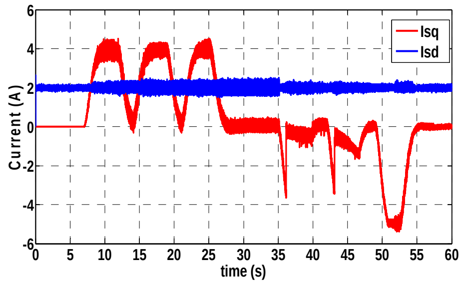
The gain scheduling scheme is applied in the IP speed controller to reduce the delay in actual speed. The results are shown in Figure 7.



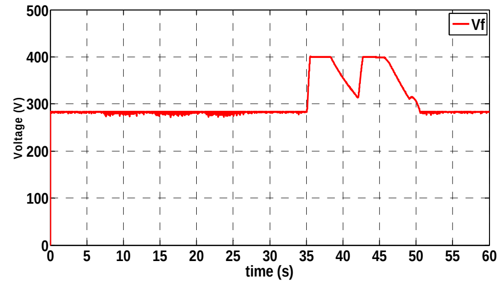
(a) Reference speed (red), actual speed (blue) and gain (green)



(b) Electric torque (red) and mechanical torque (blue)



(c) Stator current q-axis (red) and stator current d-axis (blue)



(d) DC link voltage

Figure 7 Combined regenerative and mechanical braking with gain scheduling

As shown in Figure 7(a), the delay that happens in Figure 6(a) is reduced until it reaches about 1second when the actual speed is almost same as the reference speed. Mechanical braking in Figure 7(b) is only active when the electric torque is negative and the DC link voltage is limited, so the braking system priority is regenerative braking. The DC link voltage is limited in 400 volts, as shown in Figure 7(d), to prevent the damage in the inverter components.

4. CONCLUSION

Braking methods using regenerative braking could yield overvoltage which will damage the inverter component. A voltage limiter is used to prevent overvoltage in the dc link circuit, but the actual speed does not follow the reference speed when braking. The proposed method shows that the combination between regenerative and mechanical braking could be used to compensate insufficient braking torque because of the voltage limiter. Actual speed could follow the speed reference, but there is a delay about 1.5s–2.5s in the motor speed. Therefore, by varying gain in the IP controller, the delay could be reduced about 1 second so the braking would be more accurate. Finally, the combination between regenerative and mechanical braking with gain scheduling in the IP speed controller could be used to solve the lack of braking torque when using regenerative braking with a voltage limiter.

5. ACKNOWLEDGEMENT

The authors express their gratitude to the General Directorate of Higher Education, Ministry of National Education and Culture, Republic Indonesia for supporting the research under grant contract number 2221/H2.R12/HKP.05.00/2014.

6. REFERENCES

Anne-Laure, A., Alain B., Delarue, P., Barrade, P., Chattot, E., El-Fassi, S., 2010. Energy Storage System with Supercapacitor for an Innovative Subway, *IEEE Transactions on Industrial Electronics*, Volume 57(12), pp. 4001−4012

Chapman, Stephen, J., 2005. *Electric Machinery Fundamentals*, McGraw-Hill Companies, Inc, USA

Hasegawa, I., Uchida, S., 1999. Braking Systems, *Japan Railway and Transport Review*, Japan, pp. 52−59

Jiang, J., Holtz, J., 2001. An Efficient Braking Method for Controlled AC Drives with Diode Rectifier Front End, *IEEE Transaction on Industry Application*, Volume 37(5), pp. 1299−1307

Nise, Norman. S., 2004. *Control System Engineering*, Forth Edition, John Wiley & Sons, Inc. USA

Teramoto, K., Makishima, S., Yasukawa, S., 2012. Cooperative Control of Regenerative Brake and Mechanical Brake for a Two Coach Train, *IEEE Transactions on Industrial Electronics*, pp. 1707−1712

Vas, P., 1992. *Electrical Machines and Drives: A Space Vector Theory Approach*, Clarendon Press, New York

Yusivar, F., Haratsu, H., Kihara, T., Wakao, S., Onuki, T., 2000. Performance Comparison of the Controller Configurations for the Sensorless IM Drive using the Modified Speed Adaptive Observer, *IEE-PEVD 2000,* Conference Publication No. 475, pp. 194−200

Yusivar, F., Onuki, T., 2000. *Induction Motor Drive with using Incremental Encoder, A Study of Sensorless Induction Motor Drive System for an Electric Vehicle Application*. The 1999 Master Program Thesis Waseda University, Japan, pp. 41−45

Yusivar, F., Uchida, K., Kihara, T., Wakao, S., Kondo, K., Matsuoka, K., 2001. An Anti Oscillation Strategy for the Regenerative Braking Control of Permanent Magnet Synchronous Motor with Insufficient Load Power Consumption, IECON '01, *The 27th Annual Conference of the IEEE*, Volume 2, pp. 1457−1462