Experimental Verification of Control Method to Increase Motor Power of Rail Vehicle with Onboard Energy Storage System

Hiroyasu Kobayashi [1)] **Ryuichi Tsutani** [1)]

1) Chiba University, Department of Electrical and Electronic Engineering, Graduate School of Engineering, Chiba-shi, Chiba, Japan

E-mail: h.kobayashi@chiba-u.jp

ABSTRACT: A control method of hybrid traction system which realizes increase of regenerative brake energy and reduction of consumed energy in the powering by boosting the traction motor voltage has been proposed. The proposed method includes both active HB control and energy management of onboard ESD. In this paper, the experimental verification of the proposed control method of hybrid traction system was performed utilizing 1kW class downscaled experimental setup. The experimental results show that both an accurate DC bus voltage control and energy management of the onboard ESD can be achieved by the proposed control method.

KEY WORDS: rail vehicle, energy saving, DC bus voltage boost, energy management, onboard energy storage system

1. INTRODUCTION

A hybrid traction system of railway vehicles which combines energy storage devices (ESDs) and a conventional power source has been developed(1)(2). The main purposes of this hybrid traction system are shown below.

- Storing the surplus regenerative energy
- Boosting the traction motor voltage
- Operation in an emergency situation

Effective utilization of regenerative brake energy is the first purpose of hybrid traction system. In general, regenerative energy of braking vehicle should be consumed by the other train in DC electrified railway system. If there are no powering train near the braking train, the braking train cannot utilize regenerative brake. In such case, it is possible for the hybrid traction system with onboard ESDs to store the regenerative energy, and assist the acceleration power utilizing the stored energy. This contributes to decrease the output energy of substations and save the mechanical brake wear. The second purpose is boosting the output voltage of the traction inverter. Boosting motor voltage results in increase of the traction force in the high speed region. Generally speaking, acceleration with minimum time and maximum time for coasting contribute to the energy-saving running of railway vehicle. From this point of view of energy-saving running pattern, the increase of traction force results in reduction of loss at a running resistance. Furthermore, onboard ESD can cover an operation in an emergency situation such as an escape from bridges in the case of earthquake.

A typical hybrid traction system is shown in Fig. 1. In terms of the control method of the hybrid traction system, authors have proposed a control method of hybrid traction system which realizes increase of regenerative brake energy and reduction of consumed energy in the powering by boosting the traction motor voltage (3). As shown in Fig. 2, DC bus voltage v_{fc} cannot increase independently because the traction system including the traction inverter, the traction motor and the ESS is connected to the feeder line. However, the traction system can be separated from the overhead catenary line by opening a high speed circuit breaker (HB). Considering this operation, boosting DC bus voltage can be realized. (3) proposed the control strategy of whole traction system including ESS and HB operation for the purpose of reduction of energy consumption of rail vehicle. In particular, (3) proposes a

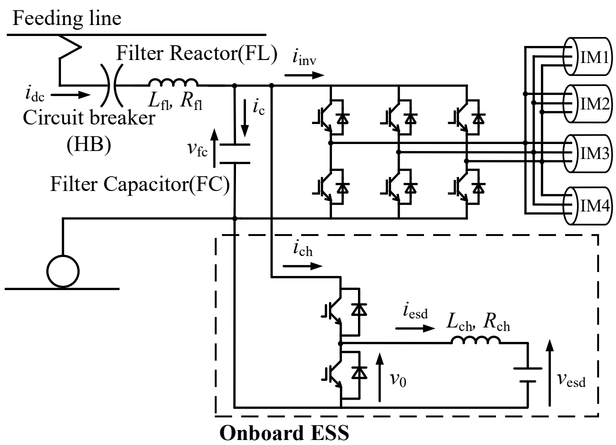


Fig. 1. Traction circuit of overhead line and energy storage device hybrid power source system.

DC bus voltage control strategy of the traction system considering both active HB operation and energy management of onboard ESD. However, the experimental verification of the proposed method was not performed in (3). In the actual control system, there are factors which are not considered in the numerical simulation such as control delay and parasitic circuit element. To evaluate the effectiveness of the proposed control method considering both an accurate DC bus voltage control and energy management of the onboard ESD even in the actual condition, experimental study should be necessary. Therefore, the experimental verification of the control strategy of the hybrid traction system is performed in this paper.

2. Control Strategy Considering Boosting Motor Voltage and Energy Management

2.1. Traction characteristics when DC bus voltage boosted

A configuration of the traction circuit which this paper focuses on is shown in Fig. 1. As mentioned in Chapter I, this paper focuses on a conventional hybrid traction system, which the onboard ESS is connected in parallel with the overhead catenary line fed by DC1600V. Fig. 2 shows a mechanism of the increase of motor power by boosting inverter output voltage. As shown in Fig. 3, both the traction force and the regenerative brake force increase in the high-speed region when DC bus voltage boost is applied. As a result, an increase of the traction power, which is equivalent to the shaded area in Fig. 2 can be expected.

2.2. Overview of a proposed Control Strategy

Based on the mechanism of the motor power increase, a novel control method for hybrid traction system including the operation of HB and ESS is introduced. The proposed control strategy of the operation of HB and DC/DC converter is shown in Fig. 3. Three control modes are considered in the proposed method. These control modes are selected according to the running state and the speed of the vehicle. Control modes are shown below.

Mode A: DC bus voltage boost mode

Mode B: Energy management mode of the onboard ESD

Mode C: Standby mode

In Mode A, HB is opened to separate the traction circuit and overhead catenary line. Simultaneously, DC bus voltage is boosted to increase motor power within the withstand voltage of the power devices in the traction circuit. This mode is utilized in the powering and braking state. On the other hand, HB is closed to connect the traction circuit to the overhead catenary line in Mode B. DC bus voltage is controlled according to the energy of the Onboard ESD in this mode. This mode is applied in the coasting

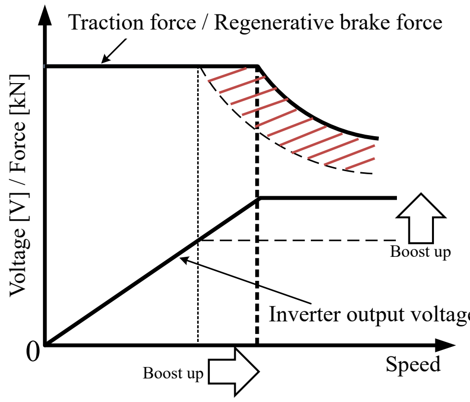


Fig. 2. Improved traction characteristics.

state to manage the energy of the onboard ESD. In Mode C, HB is closed and ESS is not activated.

2.3. Energy Management Strategy

A strategy of energy management utilized in Mode B is discussed in this section. An energy management of the onboard ESD must be required for the continuous operation because the regenerative energy is less than the energy which is necessary to increase motor voltage in the powering. Fig. 4 shows a method to determine the reference value of DC bus voltage in Mode B(11)(12). The reference of DC bus voltage v_{fc}^* is determined according to the stored energy of the ESD E_{esd} as shown in Fig. 4. Where, E_{min} and E_{max} mean minimum and maximum energy of ESD, respectively. This strategy consists of 3 areas (area A, B and C). In area B, in which E_{esd} has enough margin to both E_{max} and E_{min}, the ESS can charge or discharge as required by keeping v_{fc}^* to the middle value V_{fcmid}. In area B, v_{fc}^* is determined by (1).

$$v_{fc}^* = V_{ss} \quad \text{(1)}$$

In this paper, V_{fcmid} is equals to the no-load voltage of the substations V_{ss}. If E_{esd} becomes close to E_{min} (area A), v_{fc}^* is decreased to charge the onboard ESD from the overhead catenary line. In area A, v_{fc}^* is determined by (2).

$$v_{fc}^* = k_{el}(E_{esd} - E_{min}) + V_{fcmin} \quad \text{(2)}$$

Where k_{el} means a slope of the pattern in area A. On the other hand, if E_{esd} is close to E_{max} (area C), v_{fc}^* is increased to discharge the stored energy to the other running train. In area C, v_{fc}^* is determined by (3).

$$v_{fc}^* = k_{eh}(E_{esd} - E_{max}) + V_{fcmax} \quad \text{(3)}$$

Where k_{eh} means a slope of the pattern in area C.

Finally, the whole block diagram of DC bus voltage control system is shown in Fig. 5.

3. Experimental verification of the method of DC bus voltage boost

Running state of the vehicle	Powering			Coasting	Braking			Stop
Speed range	Low	Middle	High		Low	Middle	High	
State of HB	Open			Close	Open			Close
Control mode	Mode A			Mode B	Mode A			Mode C

Fig. 3. Proposed control method[3].

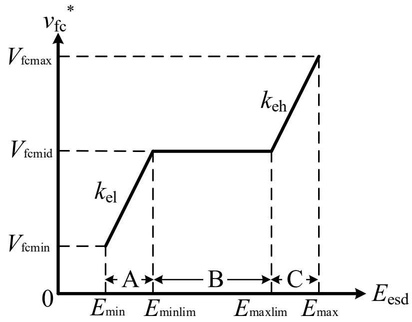


Fig. 4. A method for energy management of energy storage device.

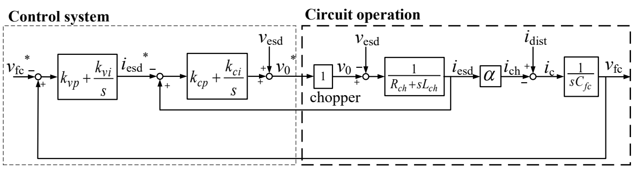


Fig. 5. Simplified block diagram of DC bus voltage control system.

3.1. Experimental conditions

Experimental setup and control system are shown in Fig. 6. Parameters in the experimental system are described in Table 1. The experimental setup is composed of substation, vehicle traction system and onboard energy storage system (ESS). In the experimental setup, MWINV-5R022 and MWINV-9R122C (Myway Plus Corp.) are utilized as the traction inverter and DC/DC converter, respectively. As shown in Fig. 6, Onboard ESD is simulated by regenerative DC power supply (biATLAS-D525: headspring Corp.). PE-Expert 4 (Myway Plus Corp.) is utilized as the control system in the experimental setup. PE-Expert 4 controls the onboard ESS, traction motor drive and the Circuit breaker operation. Induction motor is utilized as the traction motor and field-oriented-control is applied.

3.2. Experimental results

Figs. 7 – 11 show the experimental results. Fig. 7 shows rotor frequency profile. the induction motor is accelerated up to 40 Hz and start deceleration after coasting. In Fig. 7, the acceleration time in the case with v_{fc} boost is shorter than that in the case of without v_{fc} boost. This is because motor torque in higher speed region increases in the case with v_{fc} boost. Fig. 8 shows the calculated motor torque for both cases with and without v_{fc} boost.

Table 1. Specification of the traction system and control system.

Symbol	Parameters	Values
Parameters of the IM and traction system		
R_1	Stator resistance	1.735 [Ω]
R_2	Rotor resistance	1.812 [Ω]
L_1	Stator inductance	0.185 [H]
L_2	Rotor inductance	0.185 [H]
M	Mutual inductance	0.104 [H]
C_{fc}	Capacitance of FC	4.32 [mF]
L_{fl}	Inductance of FL	4.8 [mH]
R_{fl}	Resistance of FL	0.1 [Ω]
L_{ch}	Inductance of reactor of DC/DC chopper	80.0 [mH]
R_{ch}	Resistance of reactor of DC/DC chopper	0.5 [Ω]
-	Rated power of the induction motor	0.75 [kW]
-	Number of poles	6
J_m	Inertia	0.775[kgm²]
Feeder circuit		
V_{ss}	No-load output voltage of substation	200 [V]
Onboard ESS control system (ACR, AVR and Energy management)		
T_{acr}	Time constant of ACR	5.0 [ms]
T_{avr}	Time constant of AVR	50 [ms]
k_{cp}	Proportional gain of ACR	16
k_{ci}	Integral gain of ACR	100
k_{vp}	Proportional gain of AVR	0.47
k_{vi}	Integral gain of AVR	1.5
E_{min}	Assumed minimum energy of ESD	20.0 [kJ]
E_{minlim}	Threshold energy to start charge	24.0 [kJ]
E_{maxlim}	Threshold energy to start discharge	26.0 [kJ]
E_{max}	Assumed maximum energy of ESD	30.0 [kJ]
V_{fcmin}	Minimum FC voltage in Fig. 4	182 [V]
V_{fcmax}	Maximum FC voltage in Fig. 4	218 [V]

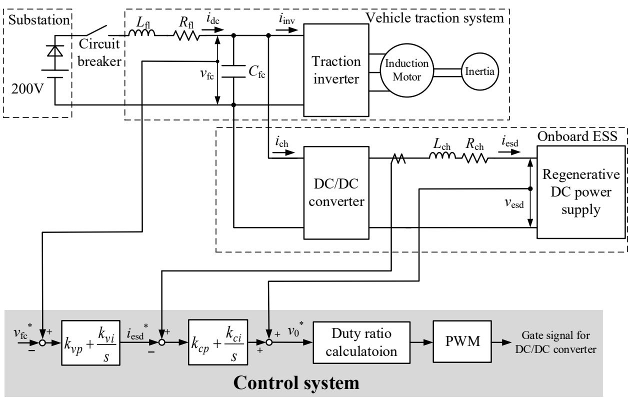


Fig. 6. Experimental setup and control system.

In Fig. 8, the constant torque region is extended in the case with v_{fc} boost. Also, reference and actual value of d- axis and q-axis current are shown in Fig. 9 (a) and (b). Fig. 9 shows both d-axis and q-axis current are regulated as the reference value. Fig. 10 (a) and (b) shows the actual and reference value of FC voltage. As shown in Fig. 10 (a) and (b), v_{fc} is controlled according to v_{fc}^*

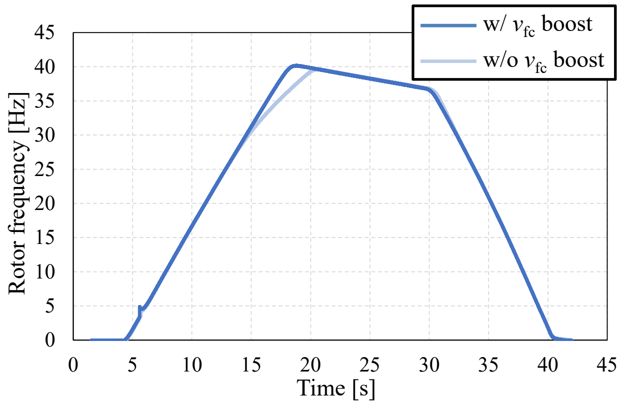


Fig. 7. Rotor frequency profile.

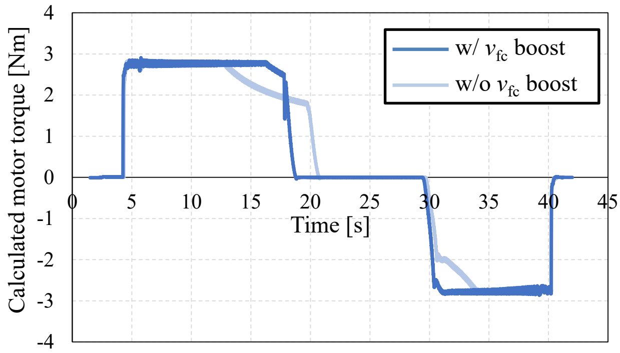
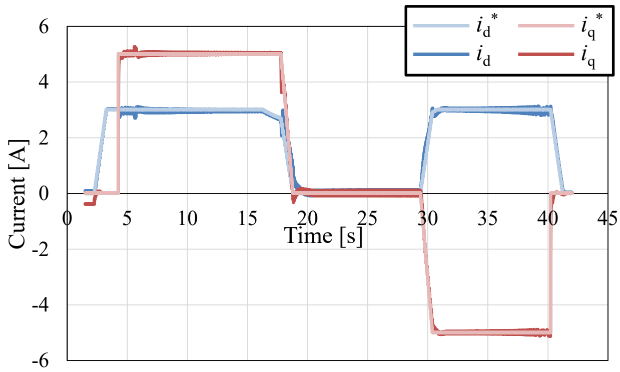
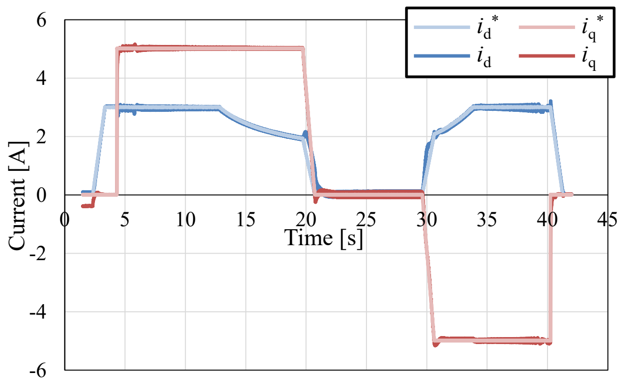


Fig. 8. Calculated motor torque waveform.



(a) w/ DC bus voltage boost

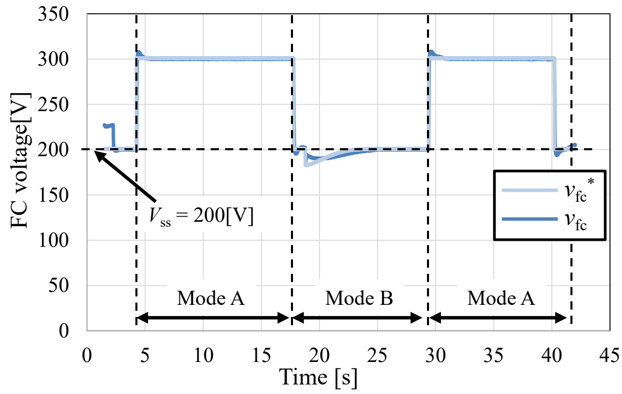


(b) w/o DC bus voltage boost

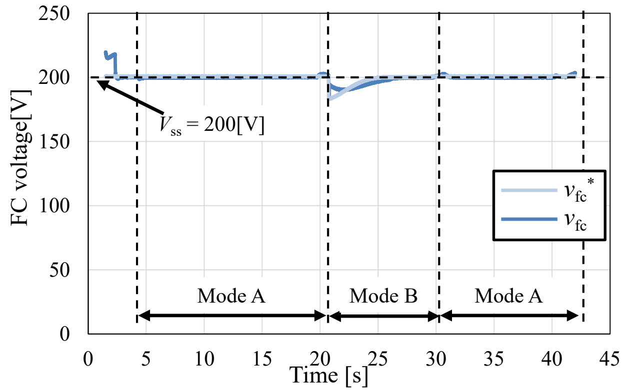
Fig. 9. d-axis and q-axis current waveform.

without large overshoot of v_{fc} in the mode transition. In Mode B, v_{fc} is controlled less than 200 V which is the output voltage of the substation to charge from the substation. This is because the energy management strategy is properly worked. As shown in Fig. 11, the energy almost returns to the initial value in single running cycle because v_{fc} decreases in Mode B by applying the energy management strategy shown in Fig. 4.

As discussed above, both an accurate DC bus voltage control and energy management of the onboard ESD can be achieved by the proposed control method. Therefore, the effectiveness of the proposed control method of the hybrid traction system is verified by the experiment.



(a) w/ DC bus voltage boost



(b) w/o DC bus voltage boost

Fig. 10. DC bus voltage waveform.

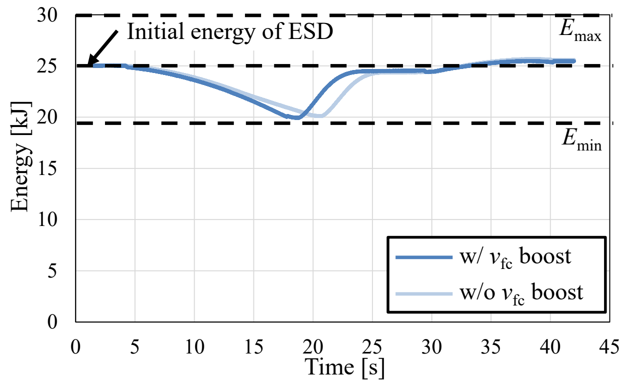


Fig. 11. ESD energy profile.

4. CONCLUSION

A control method of hybrid traction system which realizes increase of regenerative brake energy and reduction of consumed energy in the powering by boosting the traction motor voltage has been proposed. The proposed method includes both active HB control and energy management of onboard ESD. In this paper, the experimental verification of the proposed control method of hybrid traction system was performed utilizing downscaled experimental setup. The experimental results show that both an accurate DC bus voltage control and energy management of the onboard ESD can be achieved by the proposed control method.

Results in this paper contribute to establish a control system of hybrid traction system which realizes the reduction of energy consumption of rail vehicle.

REFERENCES

(1) M. Steiner, M. Klohr, and S. Pagiela, ”Energy Storage System with UltraCaps on Board of Railway Vehicles,” in Proc. 12th Eur. Conf. Power Electron. Appl. (EPE2007), pp.1-10 (2007)

(2) Y. Kono, N. Shiraki, H. Yokoyama, and R. Furuta, ”Catenary and storage battery hybrid system for electric railcar series EV-E301,” in Proc. Power Electron. Conf. (IPEC-Hiroshima 2014 -ECCE Asia-), pp. 2120–2125 (2014)

(3) H. Kobayashi and K. Kondo, “Control Method for Increasing Motor Power of DC-electrified Railway Vehicles with an Onboard Energy Storage System”, IEEJ Journal of Industry Applications, Vol. 10 Issue 5 pp. 520-527.