Charge/discharge control of a train with on-board energy storage devices for energy minimization and consideration of catenary free operation

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Abstract

The optimal operation of rail vehicle with on-board energy storage device minimizing total energy consumption is discussed in this paper. Until now, not enough research deals with the optimal control of the devices. The authors have developed the mathematical model based on a general optimization technique. In our study, the electric double layer capacitor (EDLC) is assumed as an energy storage device, because of its high power density etc. The proposed method can determine the optimal acceleration/deceleration and current commands at every sampling point under fixed conditions of transfer time and distance. The authors have also modified it for applying to catenary free operation. Using the proposed methods, simulations were implemented in some cases. The trend of optimal solutions such as values of control inputs and energy consumption is finally discussed.
Keywords: power management, on-board energy storage, optimization, energy-saving operation, supercapacitor, catenary free operation.

1 Introduction

Electrical regenerative braking has reduced total energy consumption in electric railway systems. However, if the energy is not absorbed by another train, catenary voltage rises and regenerative failure is occurred under DC power feeding system. One of the way for absorbing regenerative energy is to use energy storage. Regenerative energy is stored in the energy storage and reused in the next acceleration. The energy storage decreases the loss of circuit resistance by compensating voltage drop. It also prevents regenerative failure even if substations cannot absorb energy. Energy saving effect as well as preventing regenerative failure is expected.

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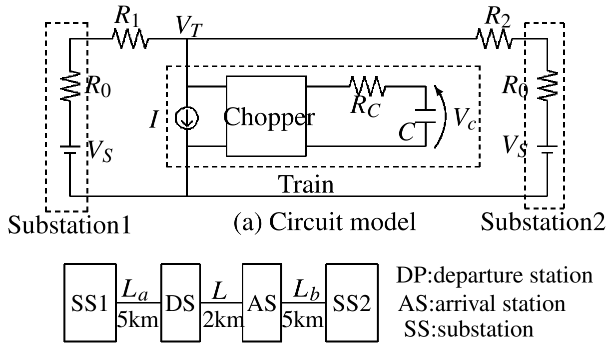


(b) Location of stations and substations

Figure 1: Modeling of a feeding circuit with one train between substations.

Some research projects on the application of the energy storage devices to railway systems have been reported in [1–6]. Most of them discussed reasonable circuit configuration and sizing of energy storage system, however, very few papers that deal with optimal charging/discharging control of the energy storage can be found. The charging/discharging command of energy storage affects the energy consumption and may influences the optimal speed profile, the trajectory of a train in the velocity-position state space. The authors pointed out that the charge/discharge command and vehicle speed profile should be optimized together. There are a few papers that deal with the energy-saving vehicle operation with a kind of optimization in [7–10]. However, they did not consider the control of energy storage.

When on-board energy storage is used, catenary free operation technique is sometimes used. Energy management control is significant in this operation because the train have to run with very limited onboard energy. However, no papers can be found that optimize train speed control.

The authors have developed the mathematical model composed of DC power feeder and energy storage that was already reported in [11]. In this paper, the authors introduce the simulation results under different condition from [11], add a few discussion to [11]. The authors also modify the model for applying to catenary free operation.

2 Modeling of energy storage and DC feeding circuit

The EDLC is assumed in the modeling of energy storage in this study. It has the characteristics of maintenance-free, long lifetime, quick charge/discharge, lower energy density than that of batteries at present, and wide range of terminal voltage regulation. The fact shows the difficulty in using EDLC as a main power source of high speed vehicles. However, if it is used with other main energy sources, the EDLC is expected as one of the most promising auxiliary devices for transportation systems.

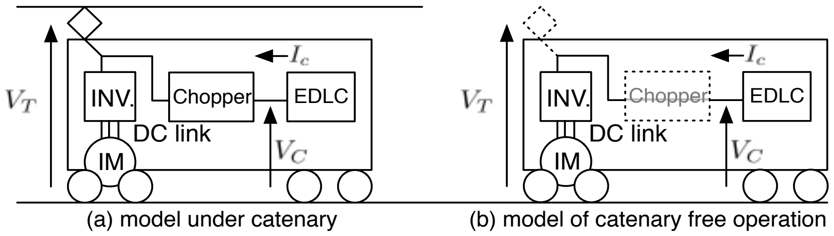


Figure 2: Circuit model of an on-board EDLC train.

A DC feeding circuit is modeled with one train between substations. The model circuit appears in Figure 2(a). In this figure, V_s and R_0 are the supply voltage and the internal resistance at a substation respectively. The values of R_1 and R_2 are equivalent resistances of feeder and return circuits. These resistance values are proportional to the distance between the train and substation. The constants C and R_c are the capacitance and internal resistance in the capacitor respectively. It is necessary to convert voltage by using a bidirectional chopper because the voltage difference between the DC link and EDLC is high. The motor-inverters of the train were modeled as a current load that helps solving circuit equations simply.

If battery is applied instead of EDLC, slight change of the model enables us to deal with the battery system. We have only to change the capacitor in Figure 1 to a voltage source and modify some equations.

3 Formulation of the operation under catenary

3.1 Definition of variables

The optimal control problem is formulated from the circuit model. Variables are defined as follows. Control inputs n and u determine the acceleration/deceleration force and charging/dischrging current, respectively. State variables x, v and V_c indicate the train position, speed and capacitor voltage, respectively. The variable V_T is the catenary voltage at the train. It is treated as an auxiliary state variable to avoid complexity in solving circuit equations analytically, although it is derived by solving circuit equations. It is derived by adding circuit equations in the optimization problem as the constraints.

3.2 Optimal control problem

The optimal control problem is described as the following mathematical formulation.

Minimizing the objective function

$$J = \int_0^T V_s I_s(x, V_T) dt \tag{1}$$

Subject to the following equality and inequality constraints

$$\dot{x} = v, \quad \dot{v} = nf_{\max}(n, v, V_T) - r(v) \tag{2}$$

$$\dot{V}_c = -I_c(u)/C \tag{3}$$

$$P_T(n, v, V_T) = P_S(x, V_T) + P_C(u, V_c) \tag{4}$$

$$x(0) = 0, \quad v(0) = 0, \quad V_c(0) = V_{c\_init} \tag{5}$$

$$x(T) = L, \quad v(T) = 0, \quad V_c(T) = V_{c\_final} \tag{6}$$

$$-1 \le (n, u) \le 1 \tag{7}$$

$$V_{T\_\min} \le V_T \le V_{T\_\max} \tag{8}$$

$$V_{c\_\min} \le V_c \le V_{c\_\max} \tag{9}$$

$$0 \le x \le L, \quad v \ge 0 \tag{10}$$

where

I_s, I_c	currents supplied from substations and EDLC current;
$f_{\max}$	maximum acceleration/deceleration force;
r	running resistance per unit weight of the train;
P_T	electric power supplied to motor-inverters of the train;
P_s, P_c	power from substations and EDLC;
$V_{T\_\min}, V_{T\_\max}$	lower and upper limitation of the catenary voltage;
$V_{c\_\min}, V_{c\_\max}$	lower and upper limitation of the capacitor voltage;
V_{c_init}, V_{c_final}	first and final values of the capacitor voltage;
L, T	distance and running time between the departure and arrival stations.

The objective function is sum of supplied energy from two substations given as (1). Equality constraints are given as (2)–(6). Equation (2) is a motion equation of the train. Gradient can be considered as including the influence to the running resistance r. The capacitor voltage is given as the (3). Equations (5) and (6) describe the initial and final conditions of state variables. The constraint (9) gives the terminal EDLC voltage as well as the initial one. Inequality constraints of control inputs, state and auxiliary variables are shown in (7)–(10).

The functions related with circuit equations are the following equations.

$$P_T(n, v, V_T) = \begin{cases} Mv \cdot nf(n, v, V_T)\eta_m & (n \ge 0) \\ Mv \cdot nf(n, v, V_T)/\eta_g(v) & (n \le 0) \end{cases} \tag{11}$$

$$P_s(x, V_T) = \left(\frac{V_s - V_T}{R_0 + R_1(x)} + \frac{V_s - V_T}{R_0 + R_2(x)} \right) \tag{12}$$

$$R_1(x) = (L_a + x)r_0 R_2(x) = (L - x + L_b)r_0 \tag{13}$$

$$P_c(u, V_c) = \begin{cases} V_c I_c(u)\eta_{ch} & (u \geq 0) \\ V_c I_c(u)/\eta_{ch} & (u \leq 0) \end{cases} \tag{14}$$

$$I_c(u) = u I_{c\_\max} \tag{15}$$

Here, η_m and $\eta_g(v)$ are motor-inverter efficiency in accelerating and braking respectively. The constant M is the total weight of the train including on-board energy storage. The regenerative efficiency η_g must be treated as the function of speed v for considering electro-pneumatic blended braking. The constant η_{ch} is the chopper efficiency assumed as constant and $I_{c\_\max}$ is the rated value of the EDLC current.

The optimal control problem is discretized using sampling time Δt and solved by the Sequential Quadratic Programming (SQP). SQP is an optimization method to solve general nonlinear programming problems. Please see [11] for the detailed procedure.

4 Consideration of catenary free operation

If the train with on-board energy storage runs off the catenary, so called catenary free operation, the mathematical formulation should be modified because the circuit topology is changed to Figure 2(b). The objective function (1) should be changed to (16) because no power is supplied from the catenary.

$$J = \int_0^T V_c I_c dt \tag{16}$$

In this study, bidirectional chopper is stopped to avoid switching loss. Then, V_T is determined by (17). The equations (11), (14) and (15) should be changed to (18), (19) and (20), respectively.

$$V_T = V_c - R_C I_c \tag{17}$$

$$P_s = I_s = 0 \tag{18}$$

$$P_c = V_c I_c \tag{19}$$

$$I_c = P_T / V_T \tag{20}$$

Some other equations such as (8) and (13) must be eliminated for topological change of the circuit.

In this operation, the control input u is finally eliminated and only the notch control input n is left. Therefore, the Dynamic Programming (DP) that was already proposed in [8] can be applied to the modified problem. Please refer [8] for details.

In the application of DP in this case, the final EDLC voltage V_{c_final} is given to implement backward search from $t = T$ to 0. The initial EDLC voltage V_{c_init} cannot be given together with V_{c_final} because the value is decided by the trajectory of n. When V_{c_init} is initially given instead of V_{c_final}, $V_c(T)$ should be adjusted so as to satisfy $V_c(0) = V_{c\_init}$.

Table 1: Specific parameters.

feeding circuit a	train operation						
Δt V_s	1[s] 1500[V]	R_0 r_0	0.03[Ω] 0.04 [mΩ/m]	η_g η_m	≤ 90 % 90 %	η_{ch} M	95% 250[Ton]
EDLC							
C I_{c_max}	32.3[F] 500[A]	V_{c_max} V_{c_min}	560[V] 300[V]	V_{c_init} V_{c_final}	560[V] 560[V]	weight R_c	500[kg] 0.3[Ω]

Another problem in using DP is that the EDLC voltage much affect accelerating/decelerating ability. The proposed method in [8] assumes this ability as constant, however, the accelerating/decelerating ability must be calculated in finding the optimal control input at each lattice point in state space.

5 Simulations of optimal operation under catenary

5.1 Condition of simulation

Specific parameters are tabulated in Table 1. In the simulations, a train runs on a straight line without speed limitations and gradients for simple analyses. The final capacitor voltage is given to equal the initial one.

In the acceleration/deceleration characteristics, electro-pneumatic blended braking system with the air supplement control is assumed. Only if the regenerative braking force is not enough for the specific braking force, air brake works. The detailed value of characteristics is shown in [11]. It is also assumed to use receptive substations that are now in the initial state of practical application for relaxation of constraints.

Two cases are prepared as tabulated in Table 2 for evaluation under various conditions. Cases A and B are the optimization of the train without and with the capacitor, respectively.

Table 2: Conditions and evaluated energy consumption in each case.

	T[s]	EDLC	minimum value of $V_c[V]$	total energy consumption [MJ]	energy saving in %
case A	120	without	–	37.56	–
case B	120	with	500	35.43	5.67
case 1	130	without	–	27.55	–
case 2	130	with	460	27.45	0.35

Cases 1 and 2 were already reported in [11].

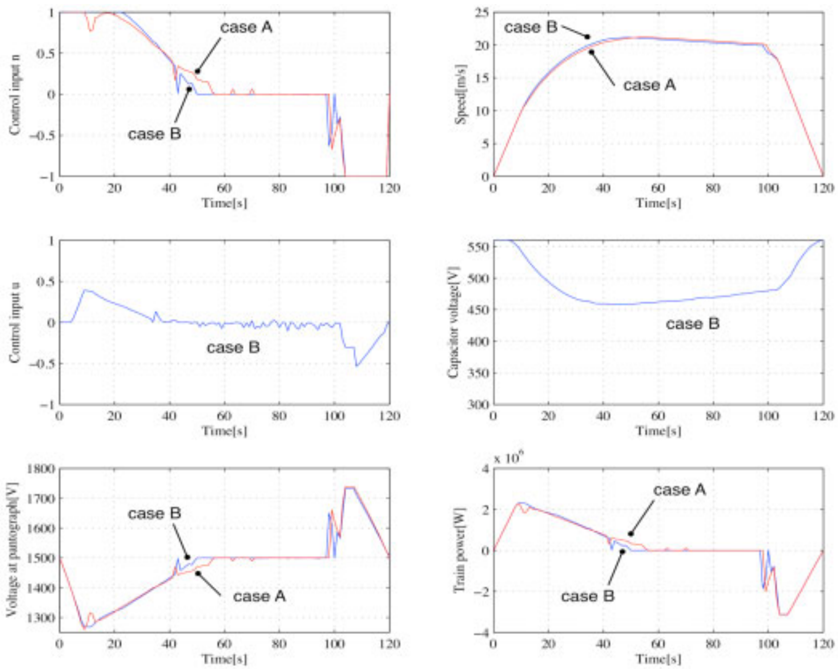


Figure 3: Graphs of optimal control inputs and state variables.

5.2 Optimization results

Optimization results are shown in Table 2 and Figure 3. In Figure 3, the graphs of control inputs n and u, catenary voltage at train pantograph, capacitor voltage, train speed, and train power at inverter input are drawn.

The optimal control input n in both cases consists of the maximum acceleration, reduced acceleration by degrees, coasting and maximum deceleration. The results are consistent with the results of previous paper [8]. Very little difference of the optimal control input n can be seen in cases A and B. Regarding the control input u, the higher the absolute value of power to the train is, the larger the absolute value of current is. Qualitatively, this trend is proper, because the energy loss by current through the feeder reduced. Substations supply the power with a small current for charging the EDLC when the train coasts.

Despite the lower limit value of the capacitor voltage $V_{c\_\min}$ is set to 300[V], the EDLC stops discharging when the EDLC voltage drops to about 460[V]. The efficiency of the capacitor itself is reduced according to the voltage drop of the EDLC.

These results can be compared with those of previously reported paper [11]. The only difference between cases A and B and cases 1 and 2 in [11] is the running time T. In [11], T is 130 [s], 10 second longer than this study. The EDLC voltage V_c, in case B, drops much lower than that in case 2. The stored energy in EDLC

Table 3: Specific parameters.

general conditions							
Δt	1[s]	η_m	70 %	η_g	$\leq$ 70 %	M	30[Ton]
EDLC							
C	40[F]	V_{c_max}	600[V]	weight	300[kg]		
I_{c_max}	500[A]	V_{c_init}	600[V]	R_c	0.1[Ω]		

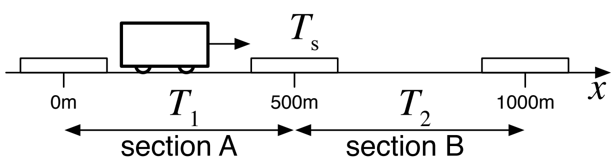


Figure 4: Running condition of tramcar.

is more effectively used in case B. Regarding energy consumption in Table 2, the energy-saving effect by introducing EDLC is 5.67%, much improved than that in [11]. From the comparison, it is derived that the shorter the margin time between stations is, the more effectively used the capacity of the EDLC.

6 Simulations of optimal catenary free operation

6.1 Condition of simulation

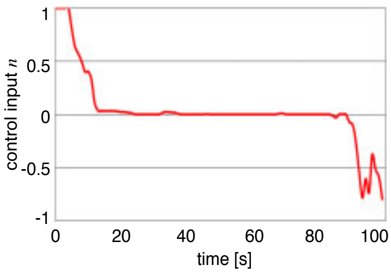
In this study for catenary free operation, a tramcar with EDLC is assumed. Specific parameters are tabulated in Table 3. The tramcar runs 1 km without suppled power from substations as shown in Figure 4. It runs within T_1 and T_2 at the sections A and B respectively and stops once between sections at $x = 500$[m] for $T_s = 10$[s].

In the simulation, the ratio of T_1 and T_2 is changed while total time $T_1 + T_2 + T_s = T_1 + T_2 + 10$ is fixed at 200[s] in order to find the optimal distribution of margin time for energy-saving operation by sensitivity analysis.

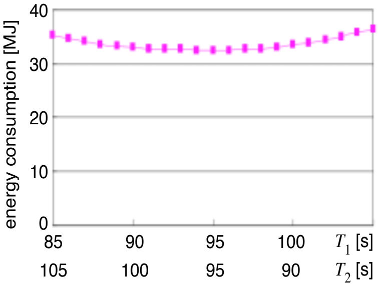
6.2 Optimization results

The simulation results are shown in Figure 5. Figure 5 (a) shows a sample of the optimal control input u in section A in case of $T_1 = 100[s]$. Figure 5 (b) is a graph that indicate relation between T_1 and energy consumption.

In this assumption of simulation, $T_1 = T_2 = 95$[s] is the condition of equal division of margin time. From Figure 5 (b), it is observed that the minimum point appears when T_1 is 95[s]. However, energy consumption in $T_1 > 95$[s] is larger than that in $T_1 < 95[s]$. The result is mainly caused by that the EDLC voltage at $x = 500$[m] is lower than that at $x = 0$[m]. If the tramcar must run faster with



(a) A sample of control input.



(b) Sensitivity analysis in changing T_1.

Figure 5: Simulation results.

lower voltage of the EDLC, larger current flowing from the EDLC increase loss by internal resistance.

7 Conclusion

This paper presents the optimal train operation with EDLC minimizing energy consumption. As a result, it is found that the energy-saving effect by using the EDLC is strongly influenced by the margin time of train schedule. On the other hand, regarding the acceleration/deceleration command, very few difference between with and without EDLC is observed.

Optimization of train speed profile in catenary free mode is also mentioned in this paper. It indicates that the distribution of margin time in each section can be optimized with the modified optimization model. The model can be used for planning of train schedule.

The knowledge extracted from the trend of optimization results will be applied to the design and parameter tuning of future charge/discharge controllers for energy storage.

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