A Numerical Algorithm for Run-curve Optimization of Trains Considering DC Feeding Circuit

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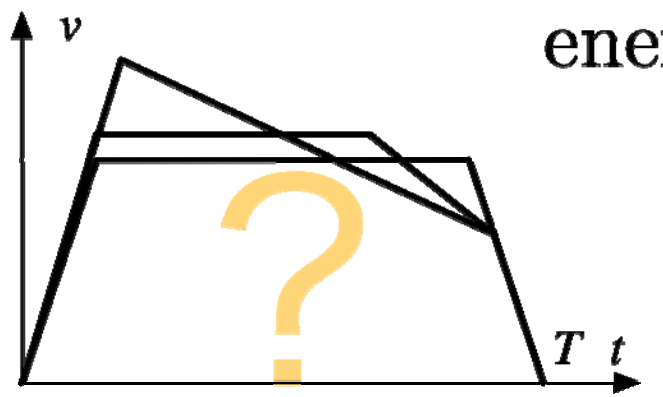
Background

- Energy-saving operation in DC railway system
  - Considering feeding characteristics and interaction among several trains is essential.
  - The system has many difficult characteristics to analyze.
  - Practical discussion of optimal train operation control has just started.

Background

- Our development of optimization techniques
  - A single train using Dynamic Programming
    - COMPRAIL 2004 by H. Ko
  - A single train with energy storage using Sequential Quadratic Programming (SQP)
    - COMPRAIL 2006 by K. Matsuda (already finished)
  - Several trains using Gradient Method
    - COMPRAIL 2006 (this presentation)



$$\text{energy} \longrightarrow \min.$$

$$T = \text{const.}$$

$$\int_0^T v\,dt = \int_0^T \int_0^T a\,dt\,dt = \text{const.}$$

Outline

Proposal of an optimization algorithm of train speed profile for practical use considering

a. Feeding circuit
b. Several trains
c. Characteristics of a train that depend on feeding voltage

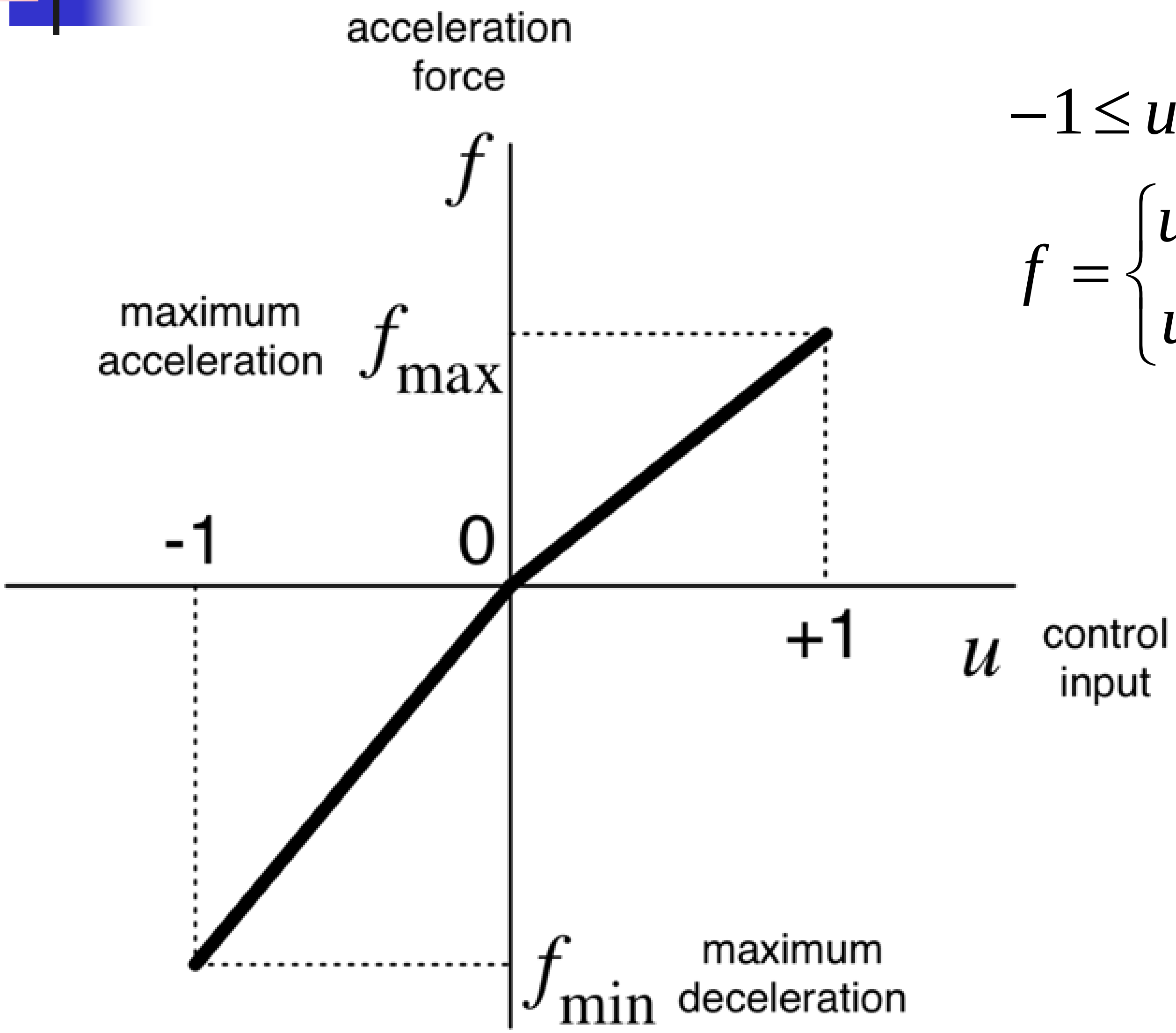
ex : Acceleration/deceleration ability, squeezing control of regenerating current and feeding loss

Mathematical formulation

Mathematical formulation is given as an optimal control problem.

- Total energy consumption at substations → Objective functional
- Kinetic equations of trains → State equations
- Circuit equations → equality constraints
- torque limitations (and speed limitations) → inequality constraints

Definition of control input u



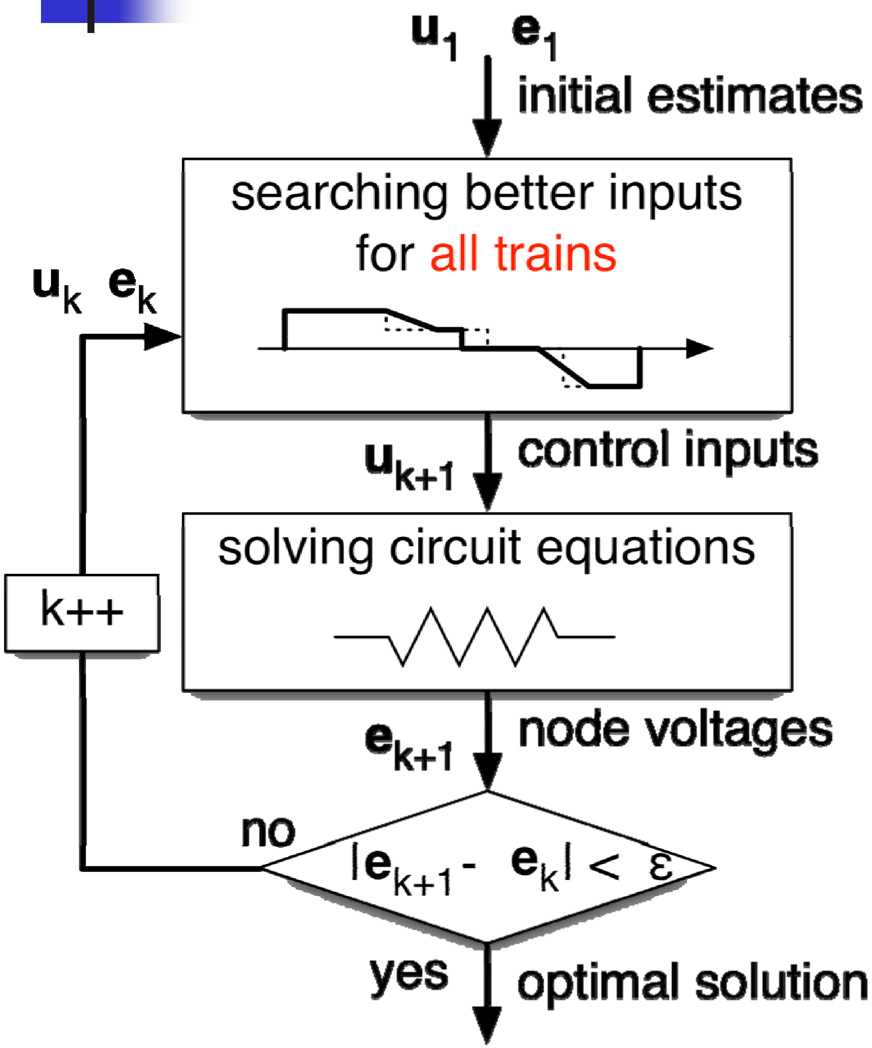
$$-1 \le u \le 1$$

$$f = \begin{cases} u f_{\max} & (u > 0) \\ u f_{\min} & (u < 0) \end{cases}$$

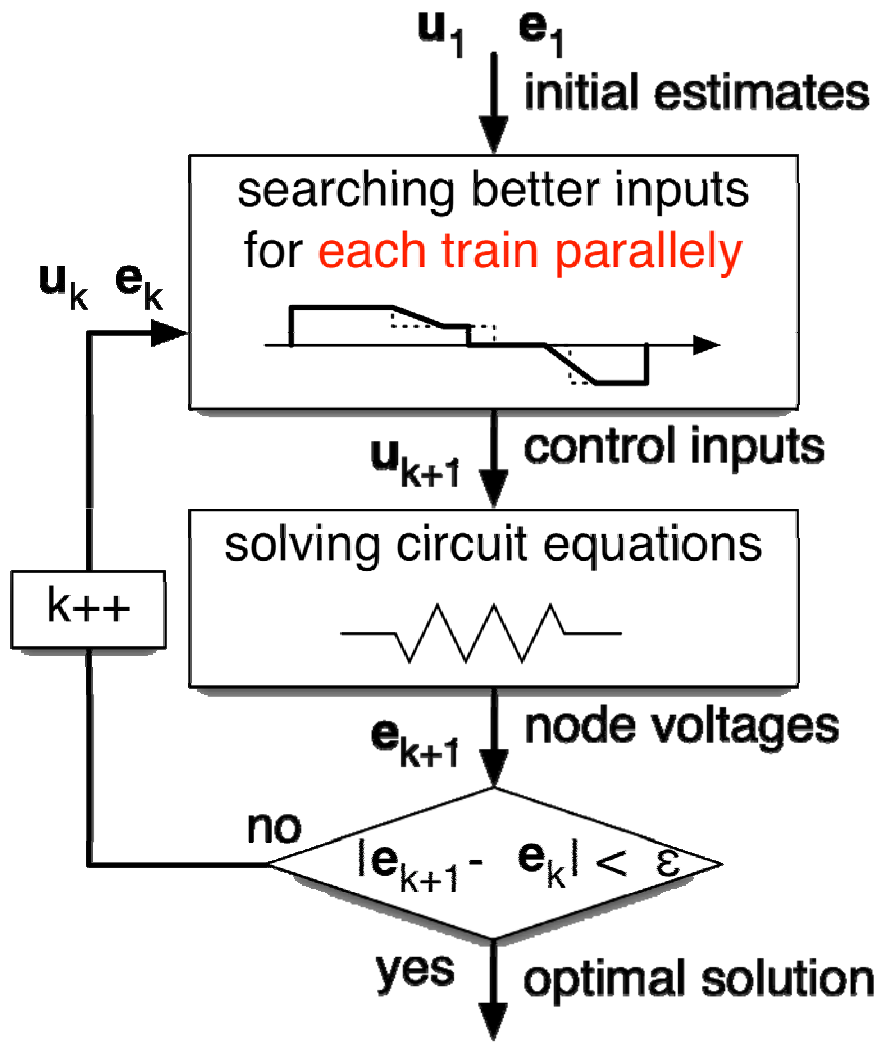
Numerical algorithms

	Algorithm I	Algorithm II
Simplicity	Worse	Better
Theoretical strictness	Better	Worse
Numerical stability	Worse	Better
Applicability to large systems	Worse	Better

Numerical algorithms



algorithm I



algorithm II

Dividing the objective functional for each trains

total energy consumption

$$J = \int_0^T \sum_{m=1}^{M} E_m(t) I_m(t) dt \rightarrow \min$$

$$= \sum_{j=1}^{N} U_j \rightarrow \min$$

T : total operating time

M : number of substations

N : number of trains

E_m : voltage of m-th substation

I_m : current of m-th substation

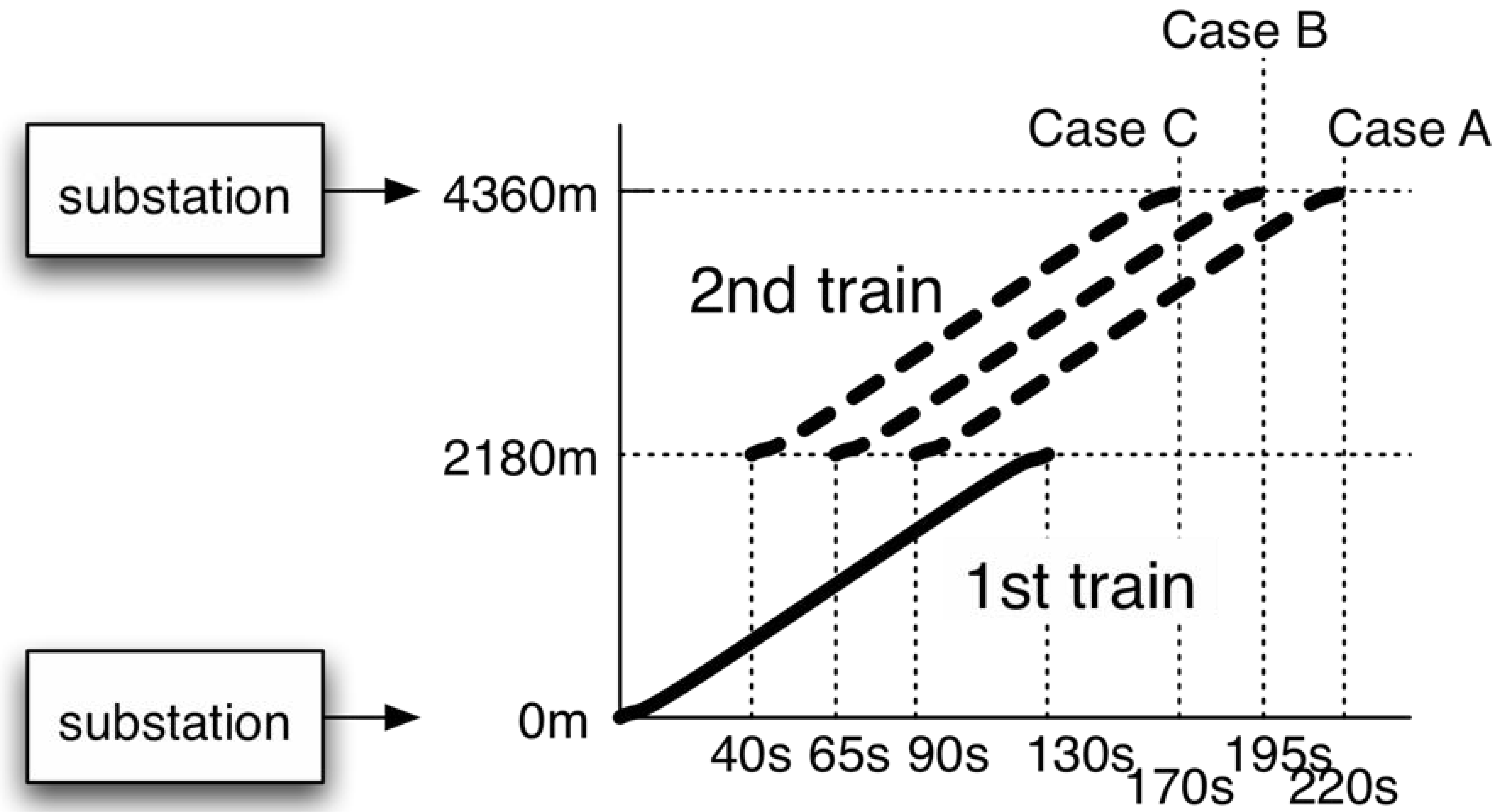
U_j : objective function of j-th train which mainly consists of j-th train's energy consumption and feeding loss

J is devided into subsets using Kirchhoff's Current Law for distributed algorithm.

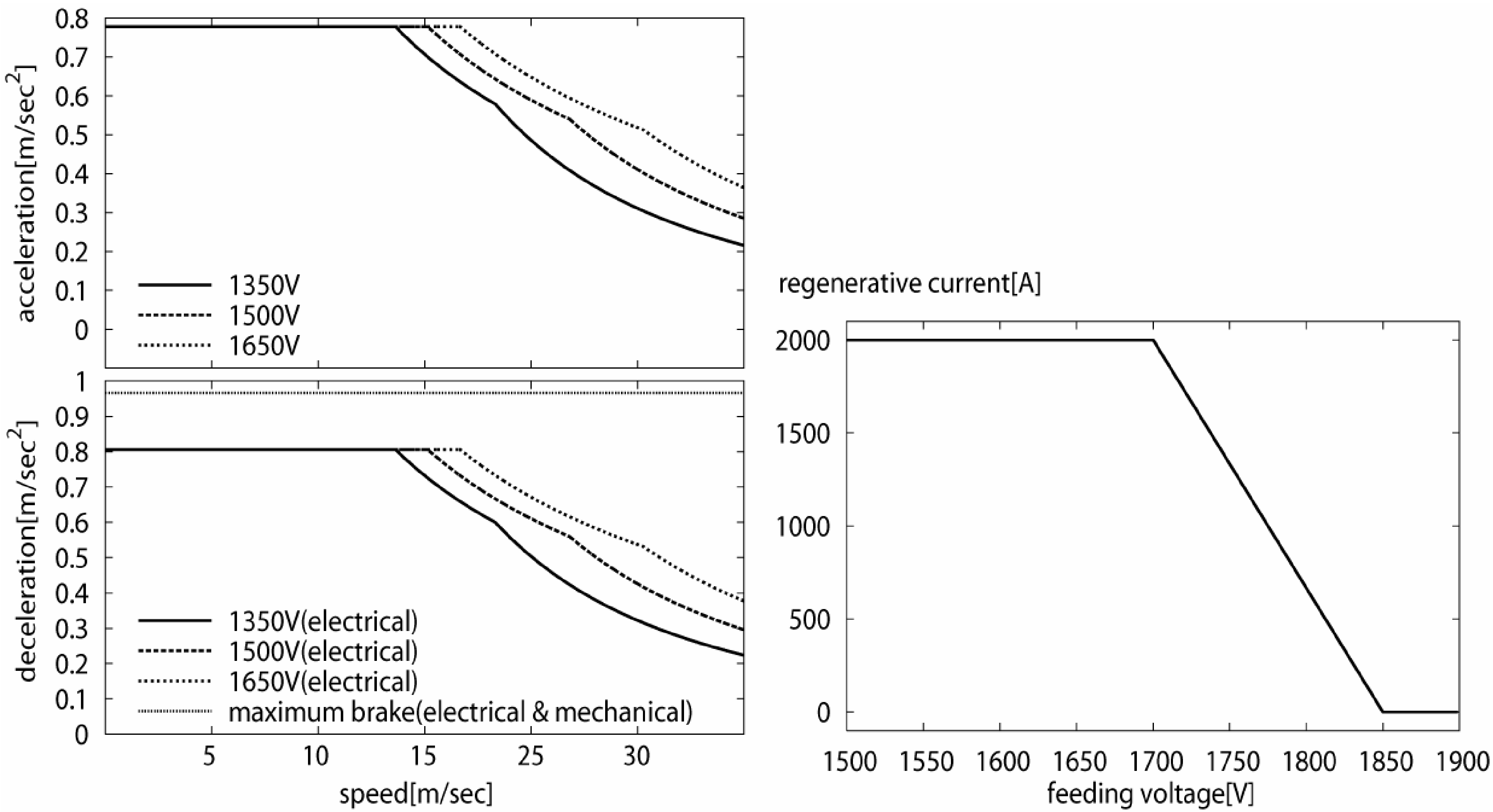
Parameters for optimizing examples

- Method : algorithm II
- PC spec : Intel Celeron 1.4GHz, 512MB
- Number of trains : 2
- supply voltage of substations E_s=1500[V]
- internal resistance of substations R_s= 0.05[Ω]
- line resistance R_l=0.04[mΩ/m]

Train movements and position of substations

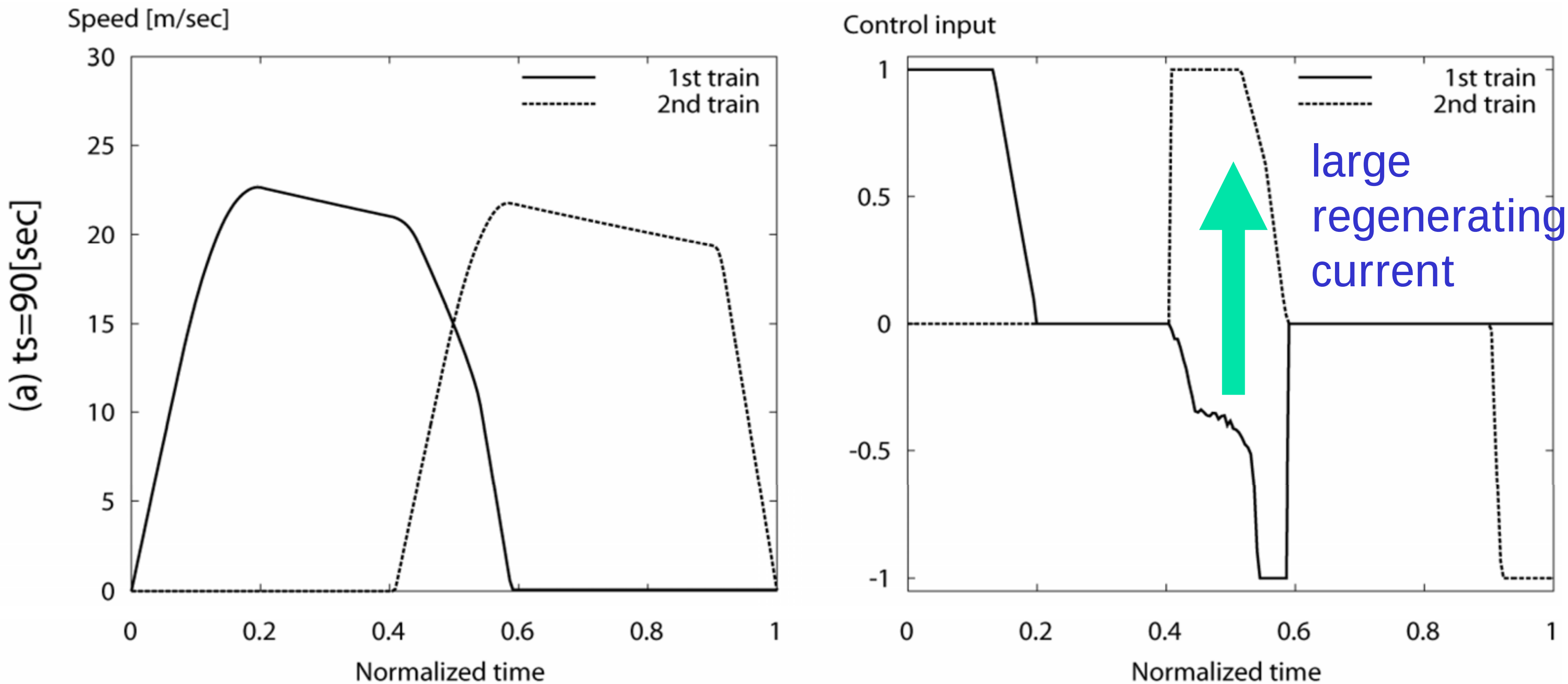


Characteristics of train



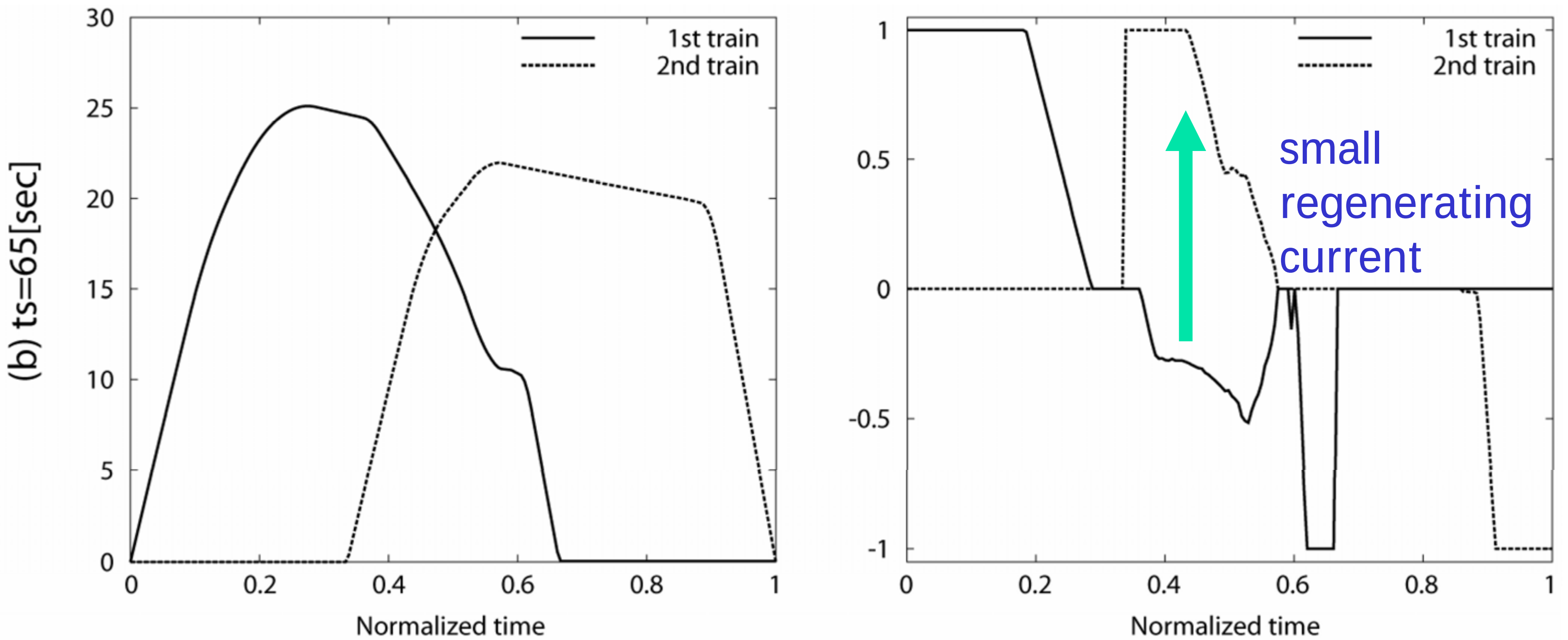
(a) acceleration/deceleration　　(b) squeezing control

Optimization results (Case A)



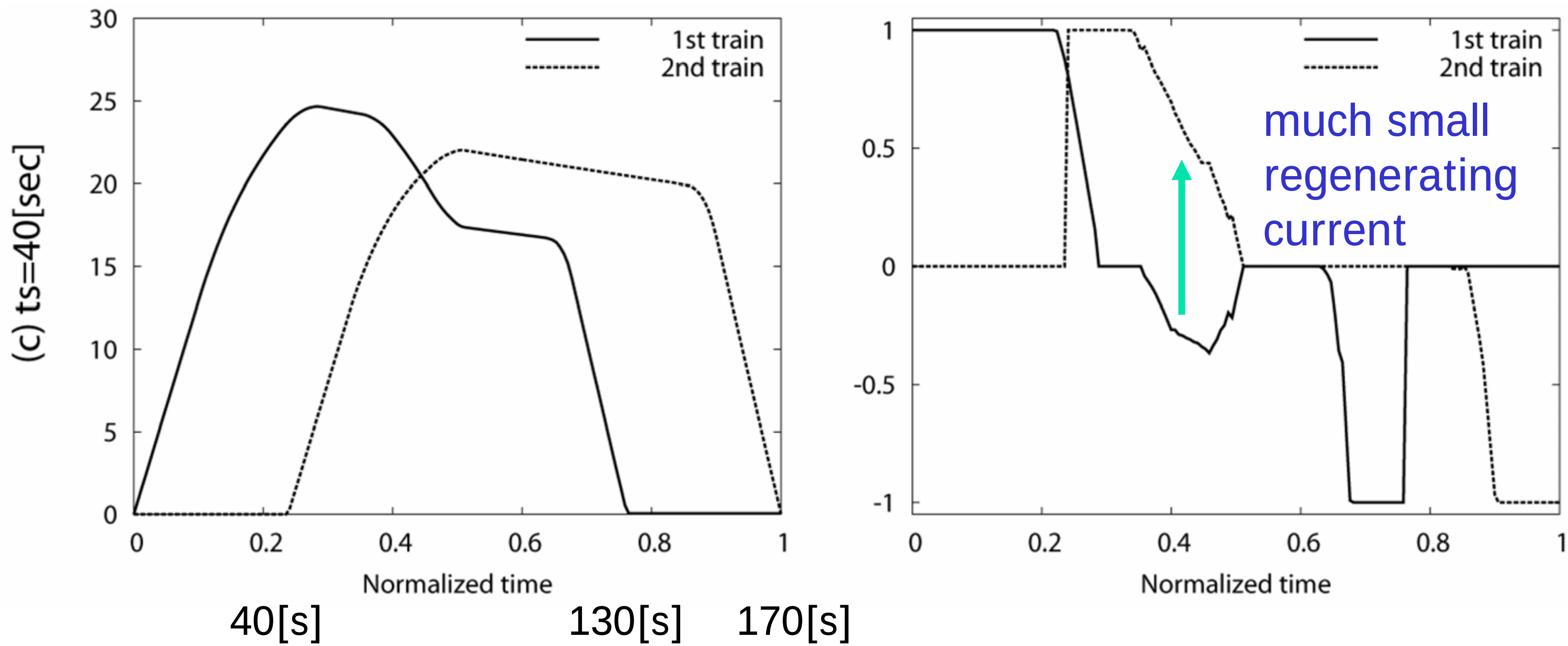
90[s] 130[s] 220[s]

Optimization results (Case B)

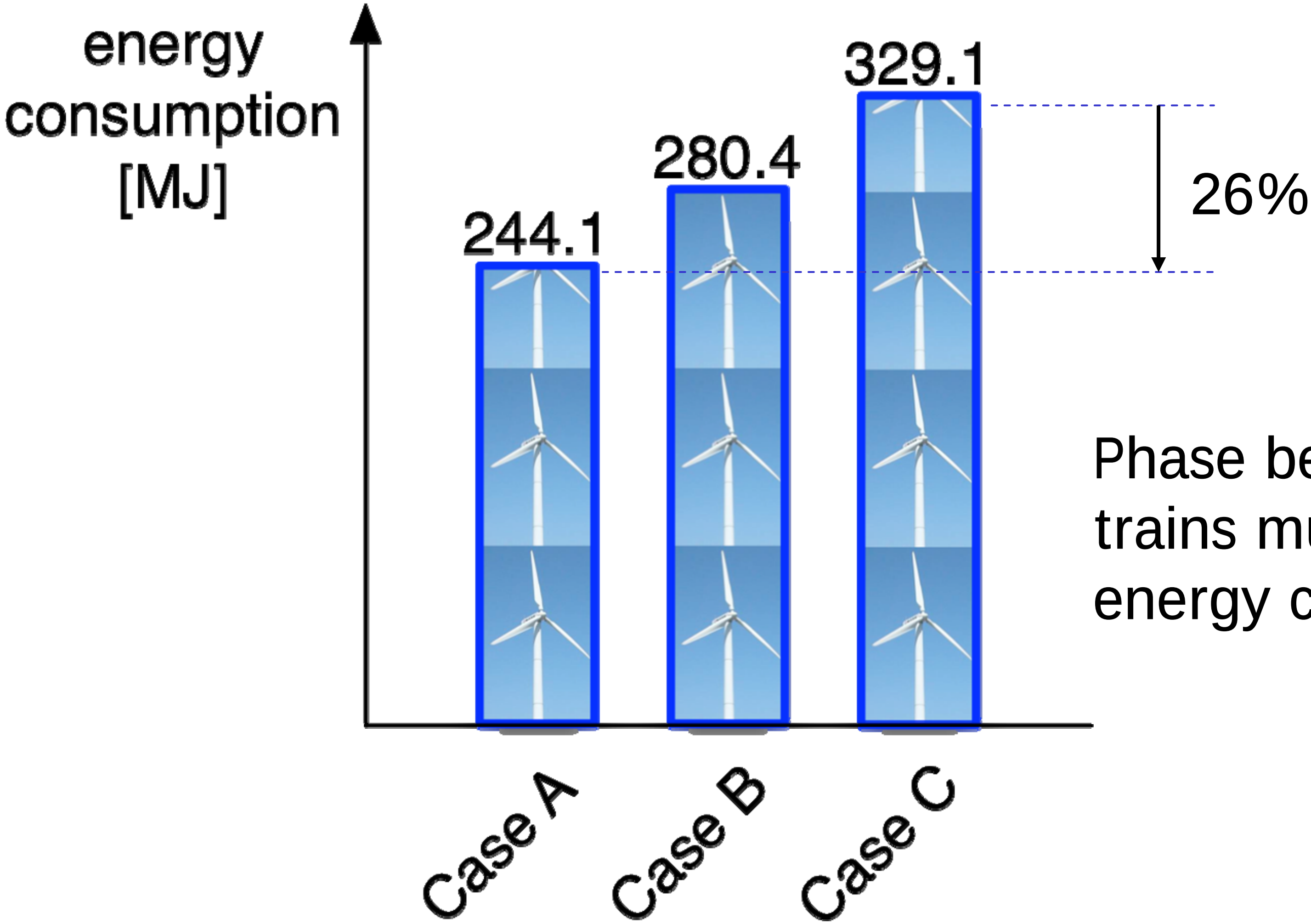


65[s] 130[s] 195[s]

Optimization results (Case C)



Energy consumption



Phase between two trains much affects energy consumption.

Summary

- The optimal operating problem of multiple trains considering DC feeding system is formulated.
- The simplified approximated numerical algorithm is performed.
- The proposed method has enough performance from numerical examples.
  - The optimal results are obtained within 1 minute