Integrated Design of Smart Train Scheduling, Use of Onboard Energy Storage, and Traction Power Management for Energy-Saving Urban Railway Operation

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This paper presents an integrated design of train scheduling, use of onboard energy storage, and traction power management for urban railways. The proposed design aims to integrate the design of train operation and infrastructure to improve energy-saving operation and the flexibility of energy management. The design problem is formulated as the minimization of the energy supplied from substations and the energy capacity of onboard energy storage. By varying the weighting factor, energy-saving purpose and cost-saving purpose can be compromised. To demonstrate the performance of the proposed design, numerical case studies are performed and evaluated on the Bangkok Mass Transit System. From the comparisons of nominal operation and design operating conditions, it is seen that the energy-saving performance is improved by up to 9.65% and the peak power at a substation is reduced by approximately 40%. The design scenario can be simply classified into cheap, moderate, and expensive designs depending on the appropriate adjusting weighting factor. Furthermore, the effect of pantograph voltage is evaluated and discussed. From the results, it is seen that the energy-saving performance is reduced by approximately 1% due to the fluctuation of the pantograph voltage. Even though the variation of pantograph voltage affects the design scheduling, a small deviation in the running time in some sections must be allowed. The proposed design still provides considerable improvement with regard to the energy-saving operations. The proposed design employs an offline design and planning because the design process requires considerable computation time.

Keywords: onboard energy storage, railway power management, regenerative power, train scheduling

1. Introduction

Nowadays, railway systems are one of the most efficient forms of transportation providing an effective use of energy and are a good solution to traffic problems. Railway systems can still utilize energy more effectively as the bulk of energy from various sources is required for operation. Therefore, the proposals on energy management and energy-saving operations are interesting issues. Design of driving strategy, train scheduling, vehicle and relevant systems are proposed as ways to improve energy usage and management in railways[1]–[2].

In modern railways, regenerative energy management has become a key for energy-saving operations. Due to the advancement of power electronic technology, regenerative braking systems can recover considerable traction energy as regenerative energy. Basically, regenerative energy is used by the train itself or it can be effectively managed by interchanging between trains based on smart train scheduling, storing and recycling based on energy storage system, and being fed back to the utility grid through an inverting substation[3]–[4].

When considering single train operation, driving strategy design provides the reduction of traction energy consumed by each train, but the mutual operation among multiple trains tends to be quite complicated when included in the design[5]–[6]. Therefore, regenerative power management has not been considered in such proposals. To improve the utilization of regenerative energy including mutual operating conditions of multiple vehicles, novel proposed strategies dealing with multi-train operation have been proposed in (7)–(11) based on maximizing the possibility of exchanging regenerative power among trains.

Furthermore, to enhance the flexibility of energy management, additional systems are introduced to develop existing railways and designing future railways. An energy storage system (ESS) is an effective option for energy management. Onboard energy storage aims to increase flexibility of energy management, reducing peak power, and enabling operation in non-electrified sections[12]–[14]. A numerical study regarding the installation of onboard batteries on trains operated in Bangkok Mass Transit System (BTS) showed the possibility for saving energy costs[15]. Wayside energy storage is expected not only to support energy-saving purpose but also enabling voltage stabilization. Optimizing control strategy, capacity and location of ESS have been proposed in (16)–(19). Energy storage provides effective energy management. Considerable additional cost may be considered for practical design. Installing an inverting substation allows for feeding of surplus regenerative energy back to the utility grid. The
operator of the connected grid must ensure that the grid can still work properly. The coordination between railway systems and the utility grid must be studied before practical application.\textsuperscript{(20)-(21)}

Combining multiple strategies into the one design process is supposed to provide better improvements of energy-saving operations and more efficient energy management.\textsuperscript{(1)} A combination of multiple methods may be carried out in an non-integrated way, i.e. each process is performed independently, or in an integrated way, i.e. multiple processes are performed simultaneously. A comparison of non-integrated and integrated design has been performed in\textsuperscript{(22)} based on integrating train scheduling and installing onboard energy storage. Integrated design provides better energy-saving performance when compared with the non-integrated method. An integrated design of energy-saving driving pattern and train scheduling based on energy-efficient algorithm was introduced in\textsuperscript{(23)}. The proposed design provides fast calculation but neglected exchanging regenerative power among trains. To consider effective energy management in multi-train operation, a cooperative train control model to design energy-saving train scheduling based on simple search algorithm was developed by\textsuperscript{(24)}. Due to the complexity of integrating various factors and parameters into the same problem, some metaheuristic methods, e.g. Genetic Algorithm, are employed to solve the problem\textsuperscript{(25)-(26)}. A two-layer optimization including timetable and driving strategy was presented in\textsuperscript{(25)}. The running times of each train were adjusted to minimize energy consumption based on the idea of synchronizing power-time profiles by using a simple estimation of energy. Moreover, an integrated optimization of driving pattern and timetable was proposed in\textsuperscript{(26)}.

To increase the flexibility of power management, integrated design of train operation and use of additional systems were proposed by\textsuperscript{(8), (27)}. An optimal design of speed profiles with consideration of regenerative energy recovery was proposed in\textsuperscript{(27)}. To manage regenerative braking energy, the application of onboard ESS was considered in the design of energy-saving speed profiles. Design of train scheduling and wayside ESS with minimizing energy supplied from substations was proposed in\textsuperscript{(28)-(29)}. The timetable parameters, location and capacity of ESS was optimized based on Genetic algorithm.

This paper presents an integrated design method for efficient railway operation by combining design of train scheduling, use of onboard energy storage, and traction power management. The proposed design aims to improve energy-saving operation by smart train scheduling based on maximizing regenerative energy usage among trains. In addition, enhancing the flexibility of energy management is enabled by active use of onboard ESS. Therefore, the design of train operating condition and design of infrastructure will be simultaneously considered in the same process. The optimization problem is formulated based on reducing energy supplied and minimizing cost of ESS. Combining train scheduling and ESS makes the problem more complicated to solve due to the complexity of objective function, the large number of decision parameters, and constraints. Therefore, Genetic algorithm is developed to solve the problem formulated in the proposed design. This paper is organized as follows.

The integrated design for determining the operating scenarios and the details of problem formulation will be explained in the second part. The main objective of the design is to minimize the energy supplied and the capacity of energy storage. Determining appropriate weighting factors, design results can be obtained with arbitrary compromise between energy-saving objectives and cost-saving objectives. In the third section, numerical case studies based on Bangkok Rapid Transit System (BTS) have been performed to verify the possibility of applying the proposed method in a practical system. After showing all evaluating results, the discussion on the results and concerns about the effect of pantograph voltage have been evaluated and compared with an ideal case in the fourth section. Finally, the paper will be concluded, and future works will also be mentioned.

2. Proposed Integrated Design

2.1 Integrated Design Concept

The proposed integrated design aims to design train scheduling, onboard ESS, and strategy of traction power management by simultaneously optimizing timetable parameters and the capacity of ESS. Employing onboard ESS, the proposed management of tractive power and regenerative power can be explained by Fig. 1. In braking mode, regenerative power will be used by onboard auxiliary systems, stored in onboard ESS, then the surplus regenerative power will be sent to nearby trains via catenary. If such regenerative power cannot be absorbed by the catenary, it will be wasted in the resister.

Besides increasing the use of regenerative power by the train itself and nearby trains, another purpose of the proposed design is to reduce the requirements of high capacity of onboard ESS. In powering mode, trains mainly consume power from the catenary and additional power from onboard ESS. For the proposed integrated design, total energy supplied from power substations is to be reduced by means of maximizing regenerative power usage. In the design of train scheduling, adjusting timetable parameters, e.g. running time and dwell time, are performed to increase the possibility of exchanging power among trains. While the timetable is being designed, the appropriate capacity of ESS is simultaneously determined based on energy-saving and cost-saving objectives.

Regarding the mutual relationship between train scheduling and ESS capacity, the strategy for utilizing regenerative power is based on onboard ESS first, then the remaining

![Fig. 1. Power Management Scheme with Onboard ESS](image-url)
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Fig. 2. Integrated Design vs Non-integrated Design

regenerative power will be managed by train scheduling. Therefore, the capacity of ESS affects the remaining regenerative power leading to the change of train scheduling. When ESS’s capacity is large, the remaining regenerative power which can be exchanged among trains is supposed to be small. Therefore, ESS’s capacity is to be minimized to provide the possibility of obtaining effective scheduling and saving the ESS’s cost.

The advantage of integrated design has been mentioned in (22). The non-integrated design is formulated as a simplified optimization and compared with the Integrated design. Basically, the non-integrated approach aims to optimize timetable parameters and capacity of ESS sequentially. The basic concept of Integrated design and Non-integrated design can be illustrated as shown in Fig. 2. The numerical case studies showed that the integrated design provides better energy-saving performance than the non-integrated design does.

2.2 Problem Formulation

The proposed integrated design is formulated as an optimization problem having objective function as shown in equation (1). The main objective aims to minimize energy supplied from traction substations and energy capacity of ESS with a variable weighting factor (w).

$$\min f(T_r, T_d, N_{ess}) = w \frac{E_{sub}}{E_{sub,base}} + (1-w) \frac{E_{ess}}{E_{ess, max}}$$

The constraints for optimization problem are determined as follows.

- **Headway limit:** $T_{h, min} \leq T_h \leq T_{h, max}$
- **Dwell time limit:** $T_{d, min} \leq T_d \leq T_{d, max}$
- **Running time limit:** $T_{r, a-b, min} \leq T_{r, a-b} \leq T_{r, a-b, max}$
- **Trip time:** $T_{trip, min} \leq T_{trip} \leq T_{trip, max}$
- **Regenerative limit:** $T_{reg} \leq V_{reg, max}$
- **ESS charge and discharge:** $SOC_{min} \leq SOC \leq SOC_{max}$

Where

- $T_a = [T_{d1}, T_{d2}, \ldots, T_{dn}]$: Dwell time,
- $T_r = [T_{r1-2}, T_{r2-3}, \ldots, T_{r(n-1)-n}]$: Running time

The estimation of relevant energy is based on the following assumptions.

- For train movement calculation, motor efficiency is assumed as constant.
- For power flow calculation, resistance per length of running rail and catenary are assumed as constant.
- For calculating voltage, the effect of pantograph voltage on traction performance is neglected. Therefore, train movement calculation and power flow calculation can be performed separately.

Based on these assumptions, the process of calculating fitness function can be simplified by using a precalculated database as shown in Fig. 3(b). To estimate energy, the power profile versus time of each train and power supply from substations will be first calculated, then the relevant energy will be estimated by numerical integration. For generating the power profile of each train, train movement calculation is performed by neglecting the effect of voltage to train performance. By assuming that all trains have the same power profile, the power profiles of multiple train operations can be simply generated by shifting the time coordinate based on corresponding timetable parameters.

To evaluate energy supplied from the substation, the power

$E_{sub}$: Estimated total energy supplied from substations (kWh), $E_{ess}$: Total energy capacity of energy storage system (kWh), $E_{reg}$: Voltage of train at pantograph in regenerative mode, $V_{reg}$: Maximum regenerative voltage, $w$: weighting factor.
flow calculation is implemented based on algorithm proposed by (30) (31). To determine nodal voltage and current at any point in the system, the power flow calculation considers exchanging regenerative power among trains and power related to ESS’s operation. Accordingly, the power flow results are used for estimating regenerative energy, charged and discharged energy of ESS, and energy supplied by substations.

To solve for the power flow calculation, the electrical models of system components are explained as follows. The train’s power and current are calculated by equation (2) and (3), respectively.

\[
P_{tr} = \begin{cases} 
\frac{F_T}{\eta} + P_{aux} & \text{Powering mode} \\
\eta \times F_B \times v + P_{aux} & \text{Braking mode} 
\end{cases} 
\]

\[
I_{tr} = \frac{P_{tr}}{V_{pant} - V_{rail}} 
\]

Where \( V_{pant} \): Nodal voltage at pantograph, \( V_{rail} \): Nodal voltage at rail conductor, \( F_T \): Tractive effort, \( F_B \): Brake effort, \( P_{aux} \): Auxiliary power, \( I_{tr} \): Train’s current, \( P_{st} \): Train’s power, \( \eta \): Motor’s efficiency.

Basically, the power substation is considered as non-inverting substation which cannot absorb regenerative power from the braking train. When, the negative current is detected, the substation will be modeled as a large resistance to limit the current.

To evaluate energy, power and SOC of ESS, the amount of power in charging mode or discharging mode for each operated train is estimated based on the control strategy shown in Fig. 4.

In powering mode, discharging power \( (P_{ess}(t)) \) and current energy stored \( (E_{ess}(t)) \) are estimated based on total power consumed by the train \( (P_{t}(t)) \) and the SOC of ESS. ESS will support the power consumed by the train with the maximum discharging capacity \( (P_{dis,max}) \). In braking mode, discharging power \( (P_{ess}(t)) \) and current energy stored \( (E_{ess}(t)) \) are estimated based on total regenerative power of the train \( (P_{reg}(t)) \) and the SOC of ESS. ESS will charge the regenerative power with the maximum charging capacity \( (P_{chag,max}) \).

2.5 Evaluation of Regenerative usage and Energy-saving Performance

1) Time period for evaluating energy quantity

Relevant energy will be calculated by integrating a power profile in a 1-hour period. Therefore, the energy quantity will be presented in kWh/hr. To demonstrate the evaluating period for calculating energy, the example of the power profile shown in Fig. 5 is illustrated with 60-minute evaluating periods.

2) Utilization of regenerative energy is defined as the ratio of energy recovered from the brake operation and total brake energy

\[
\% E_{reg} = \frac{E_{reg}}{E_{brake}} \times 100 \]

3) Energy-saving performance is defined as the percentage of substation energy which can be decreased compared with substation energy of nominal operation.
2.6 The effect of Pantograph Voltage to Train Performance

Basically, variation of pantograph voltage affects the performance of traction motor by changing the tractive effort characteristics which demonstrate the relation of speed and traction force (32). The relationship of traction force characteristics and pantograph voltage are described based on the equations (6) and (7).

\[
V_l = \frac{V}{V_N} \quad \text{(6)}
\]
\[
V_h = \frac{V}{V_N} \quad \text{(7)}
\]

Where, \(V_l\), \(V_h\), \(v_{low}\), and \(v_{high}\) are referred to the tractive effort characteristics of traction motor. \(v_{low}\) = low corner speed at current pantograph voltage, \(v_{high}\) = high corner speed at current pantograph voltage, \(v_{low}\) = low corner speed at nominal pantograph voltage, \(v_{high}\) = high corner speed at nominal pantograph voltage, \(V\) = pantograph voltage at current operating condition, \(V_N\) = nominal pantograph voltage.

3. Numerical Case Studies

3.1 Case Study Information

Bangkok Rapid Transit System (BTS-Silom line), an elevated urban electric railway operated in Bangkok, Thailand, was selected for demonstrating the integrated design case. There are 13 passenger stations along a 13-km-long double track and seven traction substations shown in Fig. 6. The system parameters for calculation are shown in Table 1.

### Table 1. Basic information of BTS silom line

| Data name                  | Information          |
|----------------------------|----------------------|
| Train’s Length             | 87.25 m (4 cars)     |
| Voltage Conditions         | nominal voltage      |
|                           | 750 V-DC             |
| Weight Conditions          | tare weight          |
|                           | 153 ton              |
| Movement Features          | max. speed           |
|                           | 80 km/h              |
|                           | max. acceleration    |
|                           | 0.87 m/s²            |
|                           | max. deceleration    |
|                           | 1.00 m/s²            |
| Efficiencies               | gear, motor, inverter|
|                           | 98%, 88%, 98%        |
|                           | regenerative brake   |
|                           | 80%                  |
| Max. Auxiliaries           | constant load        |
|                           | 270 kW               |
| Electrical Resistance      | Third-rail           |
|                           | 8.23 mΩ/km           |
|                           | Running rail         |
|                           | 40.46 mΩ/km          |
| Power substation capacity  | 2559 kVA (CEN, S02, S05, S07), 3300 kVA (S09, S11, S12) |

### Table 2. Estimated energy for nominal operation without onboard energy storage

| Traffic condition | Headway (sec) | Dwell time (sec) | Trip time (sec) | PayLoad (ton) | \(E_{peak}\) (kWh/hr) | \(E_{sub}\) (kWh/hr) | \(E_{base}\) (kWh/hr) | %\(E_{save}\) |
|-------------------|---------------|------------------|-----------------|--------------|----------------------|---------------------|----------------------|-------------|
| Peak              | 180           | 30               | 1338/1343       | 75           | 19879.25             | 9462.62             | 2848.15              | 3166.55     | 91.68       |
| Off-peak          | 300           | 20               | 1184/1188       | 38           | 6100.38              | 5703.20             | 1028.59              | 1547.38     | 66.47       |

### Table 3. Timetable parameters of nominal operation and Maximum/Minimum boundary (all values are in seconds)

| Traffic          | W1 | CEN | S01 | S02 | S03 | S05 | S06 | S07 | S08 | S09 | S10 | S11 | S12 |
|------------------|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| **Peak Hour**    |    |     |     |     |     |     |     |     |     |     |     |     |     |
| Td,min           | NA | 30  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | 30  |
| Td,max           | NA | 35  | 35  | 35  | 35  | 35  | 35  | 35  | 35  | 35  | 35  | 35  | 35  |
| Tr, nom =>       | NA | 59  | 108 | 101 | 84  | 96  | 69  | 87  | 66  | 76  | 84  | 71  | 107 |
| Tr, min =>       | NA | 56  | 103 | 96  | 80  | 91  | 65  | 83  | 63  | 73  | 80  | 68  | 102 |
| Tr, max =>       | NA | 62  | 113 | 106 | 88  | 100 | 72  | 91  | 69  | 80  | 88  | 74  | 113 |
| Tr, nom <=       | NA | 61  | 108 | 101 | 84  | 95  | 70  | 88  | 66  | 78  | 84  | 70  | 108 |
| Tr, min <=       | NA | 58  | 103 | 96  | 80  | 90  | 67  | 84  | 63  | 74  | 80  | 67  | 103 |
| Tr, max <=       | NA | 64  | 113 | 106 | 88  | 99  | 74  | 92  | 69  | 81  | 88  | 74  | 113 |
| **Off-Peak Hour**|    |     |     |     |     |     |     |     |     |     |     |     |     |
| Td,min           | NA | 20  | 20  | 20  | 20  | 20  | 20  | 20  | 20  | 20  | 20  | 20  | 20  |
| Td,max           | NA | 25  | 25  | 25  | 25  | 25  | 25  | 25  | 25  | 25  | 25  | 25  | 25  |
| Tr, nom =>       | NA | 57  | 106 | 97  | 81  | 93  | 64  | 83  | 62  | 72  | 79  | 67  | 103 |
| Tr, min =>       | NA | 54  | 101 | 92  | 77  | 88  | 61  | 79  | 59  | 69  | 76  | 64  | 98  |
| Tr, max =>       | NA | 59  | 111 | 102 | 85  | 97  | 67  | 87  | 65  | 76  | 83  | 70  | 108 |
| Tr, nom <=       | NA | 58  | 106 | 98  | 81  | 93  | 65  | 83  | 62  | 72  | 79  | 67  | 104 |
| Tr, min <=       | NA | 55  | 101 | 93  | 77  | 88  | 62  | 79  | 59  | 69  | 76  | 64  | 99  |
| Tr, max <=       | NA | 61  | 111 | 102 | 85  | 97  | 68  | 87  | 65  | 76  | 83  | 70  | 109 |
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3.3 Preparing Database of Speed and Power Profile

Based on the timetable parameters mentioned in Table 3, the profile for all possible running time in the specified range can be calculated and kept in the profile database for further use in the relevant calculating process. Because the weight of onboard ESS increases the total weight of the vehicle, the profiles of trains with different capacities of ESS will be calculated as different cases. The scenarios for calculating profile are considered as follows:
- All possible running times in a feasible boundary (only in decimal value) in all operating sections along the route (12 sections)
- Additional weights due to different capacities of ESS (1-10 kWh, decimal value)
- Different passenger loads due to traffic conditions (2 conditions, peak and off-peak conditions) and two running directions (2 directions, southbound and westbound)

The example of speed profile and power profile in the pre-calculated database are shown in Fig. 9.

3.4 Numerical Results

The case studies are simulated with two different traffic conditions and nine different weighting factors as shown in Table 4. There are 18 cases in total. Case no.1–9 are performed in peak hour period and case no.10–18 are in off-peak hour period. The specification for onboard ESS is an electrical double layer capacitor (ELDC) having 1 kWh, 300 kW, 428 kg per module (33). The minimum SOC and maximum SOC of ESS are set at 25% and 100%, respectively. The maximum regenerative voltage is limited at 900 volts and the minimum pantograph voltage is 500 volts. Parameters of GA are as follows: Maximum number of generations is 200, population is 100 times the number of variables, mutation rate is 0.8, crossover rate is 0.2. Stall generation limit is 30 with 1e-6 of fitness function tolerance. The numerical case studies are performed by using MATLAB run on a quadcore, intel core i7 with 16 GB RAM.

Variation of weighting factor from low values to high values demonstrates different design scenarios ranging from cheap infrastructure design to expensive infrastructure design. The results obtained from the proposed design, $\%E_{\text{save}}$
and \%E_{reg} are shown in Table 4. The design parameters for scheduling (i.e., OD1-OD7) are shown in Table 5.

The proposed method assumes the designed condition excluded the effect of pantograph voltage to simplify the solving process of the optimization problem, but, in practical operations, variation of pantograph voltage affects the performance of the train. Therefore, in Table 4, \%E_{save} and \%E_{reg} are evaluated by including voltage’s effect (assumed to be the same as in a practical operation) for comparison. The calculation is based on the same design driving strategy, ESS’s capacity and ESS’s control strategy.

For peak hour conditions, when the weighting factor is varied from 0.1 to 0.9, only four different scheduling results (OD1, OD2, OD3 and OD4) are obtained. From the results shown in Table 4, 4.12% of supplied energy can be saved with the cheapest design, OD1 with 1 kWh of ESS, and up to 5.87% of energy can be saved with the most expensive design, i.e., OD4 with 2 kWh of ESS.

For off-peak hour conditions, only three different scheduling (OD5, OD6, and OD7) are obtained from varying weighting factor. From the results, 5.70% of supplied energy can be saved with the cheapest design, i.e. OD5 with one ESS, and up to 9.65% of energy can be saved with the most expensive design, i.e., OD7 with 3 kWh of ESS.

The variation of the weighting factor affects the performance of designed results as shown in Fig. 10. The plot appears to reflect the low sensitivity of \%E_{save} and \%E_{reg} to the change of the weighting factor, because the same designed results are obtained from multiple weighting factors. The reason for low sensitivity is the resolution of ESS capacity which is determined as 1 kWh to reflect the practical specification of ESS modules used in practical railway application.

The sensitivity plot of \%E_{save} and \%E_{reg} to the change of weighting factor demonstrates the tendency of designed performance. When the weighting factor is changed by a considerable quantity, the different design results are obtained with better performance. When the weighting factor is changed from the minimum value to the maximum value, the weighting factor obviously affects the performance of the design results. Based on the weighting factor, the design scenarios can be classified as cheap, moderate, and expensive infrastructure design.

When the effect of pantograph voltage is considered in the calculation, \%E_{save} is reduced by 0.57% in peak hour cases and 0.93% in off-peak hour cases. The degradation of the designed performance results from the small deviation in running time which affects the efficiency of designed scheduling. The speed profile, pantograph voltage profile, the train’s power, and SOC for designed operating conditions with and without the effect of pantograph voltage are compared in Figs. 11 and 12. The voltage profile demonstrated in Figs. 11(a) and 12(a) shows the variation of pantograph voltage of a train with corresponding speed profile. The pantograph voltage always satisfies the regenerative voltage limit and minimum voltage.

The speed profile and voltage profile for the design operating condition of OD4 (peak hour) and OD7 (off-peak hour) with and without the effect of pantograph voltage are compared in Figs. 11(a) and 12(a), respectively. When the design scheduling is applied with inclusion of the pantograph voltage, the deviation of running time in some sections are observed. Such deviation entails the error in design scheduling and the decrease of \%E_{save}. The traction power and SOC of ESS with the effect of pantograph voltage are showed in Figs. 11(b) and 12(b).

From the comparisons shown in Figs. 13 (a) and (b), the effect of pantograph voltage degrades both the \%E_{save} and \%E_{reg}. The effect of voltage is more obvious when the capacity of ESS is less. Therefore, the performance in a cheap design condition entails higher sensitivity to pantograph voltage than in expensive design conditions.

When considering the power supplied by each power substation, the designed operating conditions provide a considerable reduction in peak power at substations, especially in peak hour when the peak power. As shown in Fig. 14, peak power can be reduced by approximately 43% in peak hour at substation no.2 and by approximately 41% in off-peak hour at substation no.3.

Basically, the onboard ESS can effectively suppress peak power at a substation. When the scheduling is changed, the overlap of peak power at each substation is also changed. The proposed design is aimed to reduce the capacity of ESS, but the suppression of peak power has not been included in the objective function yet. The increase of peak power compared with nominal operation may be obtained in some cases because the capacity of ESS may not be large enough to support peak power at some substations in some operating periods. Therefore, it is possible that peak power of the designed case can be higher than that of a nominal case in some substations.

Although, in case of OD1, the peak power at substation 6 is

| Traffic | Case no. | w | OD | ESS (kWh) | Without Pantograph Voltage | With Pantograph Voltage |
|---------|---------|---|----|-----------|---------------------------|-------------------------|
| Peak Hour | 1 | 0.1 | OD1 | 1 | 4.12 | 96.22 | 3.61 | 95.78 |
| | 2 | 0.2 | OD1 | 1 | 4.50 | 97.72 | 3.93 | 96.56 |
| | 3 | 0.3 | OD2 | 2 | 5.61 | 99.09 | 5.11 | 98.81 |
| | 4 | 0.4 | OD3 | 2 | 5.87 | 99.69 | 5.30 | 99.15 |
| | 5 | 0.5 | OD4 | 2 | 5.70 | 78.96 | 4.77 | 76.52 |
| | 6 | 0.6 | OD5 | 2 | 6.93 | 89.49 | 5.98 | 88.81 |
| | 7 | 0.7 | OD6 | 2 | 9.65 | 98.05 | 8.88 | 97.75 |
| | 8 | 0.8 | OD7 | 3 | 9.65 | 98.05 | 8.88 | 97.75 |
| Off-peak Hour | 9 | 0.9 | OD1 | 1 | 4.12 | 96.22 | 3.61 | 95.78 |
| | 10 | 0.1 | OD2 | 2 | 5.70 | 89.49 | 5.98 | 88.81 |
| | 11 | 0.2 | OD3 | 2 | 8.37 | 98.05 | 8.88 | 97.75 |
| | 12 | 0.3 | OD4 | 2 | 9.65 | 98.05 | 8.88 | 97.75 |
| | 13 | 0.4 | OD5 | 2 | 9.65 | 98.05 | 8.88 | 97.75 |
| | 14 | 0.5 | OD6 | 2 | 9.65 | 98.05 | 8.88 | 97.75 |
| | 15 | 0.6 | OD7 | 3 | 9.65 | 98.05 | 8.88 | 97.75 |
| | 16 | 0.7 | OD1 | 1 | 4.12 | 96.22 | 3.61 | 95.78 |
| | 17 | 0.8 | OD2 | 2 | 5.70 | 89.49 | 5.98 | 88.81 |
| | 18 | 0.9 | OD3 | 2 | 8.37 | 98.05 | 8.88 | 97.75 |

Table 4. Designed results and evaluation of \%E_{save} and \%E_{reg} of all case studies
Table 5. Designed timetable for all case studies (all values are in seconds)

| Name | W1 | CEN | S01 | S02 | S03 | S05 | S06 | S07 | S08 | S09 | S10 | S11 | S12 |
|------|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| OD1  | Td => | NA  | 30  | 30  | 30  | 31  | 31  | 31  | 31  | 31  | 31  | 31  | NA  |
|      | Tr => | NA  | 58  | 106 | 97  | 81  | 96  | 71  | 84  | 67  | 77  | 87  | 106 |
| OD2  | Td => | NA  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | NA  |
|      | Tr => | NA  | 61  | 107 | 97  | 82  | 94  | 71  | 85  | 68  | 77  | 86  | 108 |
| OD3  | Td => | NA  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | NA  |
|      | Tr => | NA  | 62  | 103 | 97  | 80  | 93  | 72  | 84  | 69  | 81  | 88  | 110 |
| OD4  | Td => | NA  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | NA  |
|      | Tr => | NA  | 60  | 106 | 99  | 81  | 93  | 71  | 82  | 68  | 78  | 87  | 107 |
| OD5  | Td => | NA  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | NA  |
|      | Tr => | NA  | 62  | 103 | 97  | 81  | 91  | 72  | 86  | 69  | 81  | 87  | 107 |
| OD6  | Td => | NA  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | NA  |
|      | Tr => | NA  | 50  | 101 | 95  | 83  | 90  | 71  | 81  | 69  | 75  | 83  | 106 |
| OD7  | Td => | NA  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | 30  | NA  |
|      | Tr => | NA  | 59  | 103 | 98  | 80  | 93  | 71  | 80  | 64  | 74  | 83  | 101 |

Fig. 10. % $E_{\text{save}}$ and % $E_{\text{reg}}$ vs Weighting Factor without effect of pantograph voltage

increased less than 0.5 MW when compared with the nominal case, the peak power at substation 2 and 3 decreased considerably. In the case of off-peak hour, the peak power at substation 5 increased in both cases, OD5 and OD7, while the peak power at substation 3 was suppressed considerably.

4. Discussions

4.1 Determining Weighting Factor The weighting factor is designed for compromising the energy-saving and the cost-saving objectives. The variation of weighting factor provides different design conditions depending on the requirements of the operator. The large weighting factor represents the expensive infrastructure design, while decreasing the weighting factor tends to reduce the cost of infrastructure or additional systems. However, various designed results obtained from varying weighting factors may overlap depending on the resolution of possible designed capacity of ESS. The design scenarios may be classified as a few different scenarios, i.e. cheap infrastructure design, moderate infrastructure design, and expensive infrastructure design.

4.2 The Effect of Pantograph Voltage Basically, the variation of pantograph voltage directly affects the performance of the traction system. To simplify the problem solved in the proposed design, the optimization process disregarding the voltage effect may provide nonpractical solutions. From the comparison between the numerical results...
with and without the effect of voltage, the variation of voltage in an acceptable range entails some small errors in the design scheduling that may degrade the energy-saving performance. Therefore, a small deviation in some running sections may be allowed if the design scheduling and speed profiles are applied for in the system operation without any modification.

4.3 Concerns Regarding Application of the Proposed Method

The integrated design aims to maximize the utilization of regenerative energy by combining smart scheduling and use of onboard energy storage. Generally, urban railways operated in peak hour periods or small headway periods have good utilization of regenerative energy. Therefore, the proposed design tends to be ineffective at improving energy-saving performance but reducing the peak power at a substation may be advantageous. The system operating in off-peak periods or larger headway periods obviously has the possibility to obtain more effective regenerative energy management. From the numerical results, the design operating condition provides better improvement on energy-saving performance when compared with nominal operations.

5. Conclusions

This paper presents the integrated design of train scheduling, use of onboard energy storage, and traction power management. The main objective is to combine the design of train operation and infrastructure to improve energy-saving operations and the flexibility of energy management. The design solution is based on minimizing energy supplied from
substations and the energy capacity of onboard ESS. Moreover, energy-saving and cost-saving purposes can be compromised by varying weighting factor. From the numerical results evaluated in the case studies of the BTS, the design timetable parameters and appropriate capacity of ESS obtained from the proposed design can provide improvement of energy-saving performance of up to 9.65% when compared with nominal operation and can reduce the peak power at a substation by approximately 40%. The design scenario can be simply classified as cheap, moderate, and expensive depending on variations of the weighting factor.

From the case studies, when peak hour (3-minute headway) is considered as part of the design condition, utilizing the designed scheduling and increasing ESS’s capacity from 1 kWh to 2 kWh provided an improvement of energy-saving performance from 4.12% to 5.87%. In the case of off-peak hour (5-minute headway), the energy-saving performance can be improved from 5.7% to 9.65% by upgrading ESS capacity from 1 kWh to 3 kWh with the designed scheduling.

Furthermore, the effect of pantograph voltage has also been evaluated and compared with an ideal case and the results indicate that when the effect of voltage is included in the calculation, energy-saving performance is degraded due to some small errors in the design scheduling. When the effect of pantograph voltage is considered, the energy-saving performance in peak hour and off-peak hour is degraded to 5.30% and 8.88% respectively. The variation of train voltage affects the design scheduling and some small deviations in running time of some sections may be allowed. The application of proposed design still provides considerable improvement in energy-saving operation. From the comparisons, we see approximately 1% of energy-saving is reduced due to the voltage effect.

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