Efficient Urban Railway Design Integrating Train Scheduling, Wayside Energy Storage, and Traction Power Management

Warayut Kampeerawat* a) Student Member, Takafumi Koseki Member

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This paper presents a design of efficient urban railways based on an integrated design of train schedule and use of wayside energy storage. The main objective is to simultaneously design the train operation, infrastructure, and traction power management scheme to enhance energy-saving operation and the flexibility of energy management. The proposed design aims to minimize the energy supplied from substations and the energy capacity of the energy storage system (ESS). The objective function is formulated as the weighted sum of the energy-saving term and cost-saving term. Numerical case studies are performed on the Bangkok mass transit system (BTS) to demonstrate the performance of the proposed design. From the results, it is seen that the designed timetable parameters and the appropriate installation scenario of ESS (i.e. capacity and location) obtained from the proposed design can improve the energy-saving performance by up to 10.35% compared with the nominal operation. Moreover, the reduction of peak power and voltage regulation at substations can be achieved. By adjusting the weighting factor, the design scenario can be classified into categories ranging from a cheap infrastructure design to an expensive design; and the decision of an optimal solution can be simply finalized by considering the Pareto curve. To simplify the optimization process, the effect of voltage is excluded. Therefore, the performance of the design operation may be degraded by the variation of the pantograph voltage. From the comparison, it is seen that the variation of voltage entails small deviations in the design scheduling and degrades the energy-saving performance, especially in the off-peak hour condition. Even though such deviations are allowed in the operation of some running sections without any modification of the designed condition, the energy-saving performance is still improved.

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

1. Introduction

Currently, modern railway systems are one of the most effective means of transportation in regards to energy efficiency and environmental friendliness. Improving railway operations to be more efficient is a prominent issue in the railway research field. Various techniques, e.g., design of driving strategy, smart train scheduling, development of vehicle and relevant systems are proposed(1)–(6). Various optimization techniques, e.g. dynamic programming and heuristic search are applied for the design of the speed profile with minimum energy consumption. In a practical operation, the mutual operation among multiple trains directly affects operation and control of each train and its relevant system. To develop an efficient driving strategy for practical operation, a design of train control strategies with a focus on regenerative power management among trains has been proposed in (7)–(11).

Moreover, the flexibility of power and energy management can be realized by utilizing additional systems, e.g. an energy storage system. Energy storage systems (ESS) are introduced as an effective solution for enhancing railway energy management. Using onboard energy storage can provide flexibility in energy management, reduction of peak power, and enable the operation of non-electrified sections(12)–(14). In (15), a performance evaluation of onboard batteries installed on an urban railway operated in Bangkok, Thailand was performed numerically, and the results showed that considerable savings in energy costs can be achieved. Installing energy storage as a wayside or trackside infrastructure aims to enhance energy management and improve power quality(16)–(17). Utilizing additional systems, the considerable cost of infrastructure is the main obstacle. To optimize the cost for application of energy storage, optimization problems dealing with the reduction of ESS’s capacity have been proposed in (18)(19). Furthermore, an inverting substation is an interesting wayside infrastructure which enables the feeding of surplus regenerative energy back to the utility grid. Coordination between the railway system and utility grid must be carefully evaluated to
prevent the power quality problem (20)-(21).

Deploying multiple methods and active use of additional systems into one railway system can improve both energy-saving performance and the flexibility of power management. Multiple approaches may be combined by means of non-integrated or integrated ways. Combination of train schedule design and use of onboard energy storage has been proposed in (22) and a comparison of non-integrated design and integrated design was performed. Based on the proposed integrated design, both design of train schedule and design of installing energy storage were simultaneously performed. Compared with non-integrated design, the Integrated design provides better energy-saving performance. Mentioned in (23), integrated design of the energy-saving speed profile and train schedule was proposed. The proposed design applies an efficient algorithm providing fast calculation but neglects exchanging regenerative power management. In consideration of effective energy management in multi-train operation, a cooperative train control model to design an energy-saving train schedule was developed in (24). Some metaheuristic methods, e.g. Genetic Algorithm are employed to cope with the complex design problems including various factors and parameters (25)-(26). A two-layer optimization including timetable and driving strategy was introduced in (25). To synchronize the power-time profile with simplified assumptions, energy consumption is supposed to be minimized by adjusting running times of each train. Furthermore, a combination of driving control design and train scheduling was proposed in (26).

Driving control design integrating the use of additional systems was proposed in (27). An evaluation of applying the proposed driving controls and utilization of some additional systems for energy management showed performance in saving energy and operating cost in practical usage. Integrated design of the train schedule and application of wayside ESS was proposed in (28)-(29). The problem is formulated as a multi-objective optimization which aims to minimize energy supplied and capacity of ESS and the simplified case studies have been performed to show the performance of the proposed design.

This paper presents an integrated design method for efficient railway operation by combining train schedule design, use of wayside ESS, 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 achieved by an active use of wayside ESS. The design of train operating condition and design of infrastructure are to be simultaneously considered in the same process. The optimization problem is a multi-objective problem with two objectives, i.e., minimizing energy supplied and minimizing cost of ESS. The proposed objective function is formulated as a weighted sum of the two objectives and it is solved by Genetic Algorithms. To evaluate the performance of the proposed design, numerical case studies based on Bangkok Rapid Transit System (BTS) have been performed. This paper is organized as follows. The integrated design for determining the operating scenarios and the detail of problem formulation will be explained in section 2. Results of case studies based on practical operating condition have been explained in section 3 and the discussions on the results and concerns about the effect of pantograph voltage have been evaluated and compared with ideal cases in section 4. Finally, the paper is concluded, and the future work is mentioned.

2. Proposed Integrated Design

2.1 Integrated Design Concept

The proposed integrated design aims to design the train schedule, wayside ESS, and a management strategy of traction power by simultaneously optimizing timetable parameters and capacity of ESS. The concept of integrated design can be illustrated as Fig. 1. The proposed management of active use and regenerative power can be explained by Fig. 2. In braking mode, regenerative power will be used by onboard auxiliary systems, then the surplus regenerative power will be sent to nearby trains via catenary. The remaining regenerative power is to be absorbed by wayside ESS. Finally, if such regenerative power cannot be absorbed by the catenary, it will be wasted in the resistor. The main purpose for increasing the use of regenerative power for the train itself and nearby trains is to reduce the requirement of high capacity wayside ESS. Trains mainly consume power from the catenary and additionally from wayside ESS.

For the proposed integrated design, total energy supplied from power substations is to be reduced by means of maximizing regenerative power usage. For the train schedule design, adjusting timetable parameters, e.g. running time and dwell time, was carried out to increase the possibility of exchanging power among trains. Train schedule and the appropriate location and capacity of ESS are simultaneously determined based on energy-saving and cost-saving objectives.

2.2 Problem Formulation

The proposed integrated design aims to simultaneously minimize the energy supplied from traction substations and minimize energy capacity.
of ESS. Therefore, the problem is formulated as a multi-objective optimization problem having two objectives. To obtain the optimal solution, the objective function is developed as the weighted sum of normalized objective functions as shown in (1).

\[
\text{min } f(T_r, T_d, L_{ess}, E_{ess}) = w \frac{E_{sub}}{E_{sub\_base}} + (1 - w) \sum_{i=1}^{m} \frac{E_{ess\_i}}{E_{ess\_i\_max}} \quad \cdots \cdots \quad (1)
\]

The constraints for the optimization problem are determined as follows.

- **Headway limit:** \( T_{h, min} \leq T_h \leq T_{h, max} \)
- **Dwell time limit:** \( T_{d_{a\_min}} \leq T_{d} \leq T_{d_{max}} \)
- **Running time limit:** \( T_{r_{a\_b_{min}}} \leq T_{r_{a\_b}} \leq T_{r_{a\_b_{max}}} \)
- **Trip time:** \( T_{trip_{a\_b_{min}}} \leq T_{trip} \leq T_{trip_{a\_b_{max}}} \)
- **Regenerative limit:** \( V_{tr_{reg}} \leq V_{reg\_max} \)
- **ESS charge and discharge:** \( SOC_{min} \leq SOC \leq SOC_{max} \)

\[
V_{ess\_char} \leq V_{ess\_dis} \leq V_{dis\_char} \leq V_{dis\_stop}
\]

Where

\[
T_d = [T_{d_{1}}, T_{d_{2}}, \ldots, T_{d_{n}}] : \text{Dwell time,}
\]

\[
T_r = [T_{r_{1\_2}}, T_{r_{2\_3}}, \ldots, T_{r_{(n-1)\_n}}] : \text{Running time}
\]

- **Headway (s),** \( T_d : \) Dwell time at passenger station \( a(s)\), \( T_{r_{a\_b}} : \) Running time from passenger station \( a \) to station \( b(s)\), \( T_{trip} : \) Trip time for single journey of a train \((s)\), \( E_{sub} : \) Estimated total energy supplied from substations \((kWh)\), \( E_{sub\_base} : \) Estimated total energy supplied from substations \((kWh)\) in case of nominal operating condition, \( E_{brake} \): Estimated total energy generated from electrical brake system \((kWh)\), \( E_{reg} \): Estimated total regenerative energy utilized by trains \((kWh)\), \( E_{ess} \): Total energy capacity of energy storage system \((kWh)\), \( E_{ess\_max} \): Maximum energy capacity of energy storage system \((kWh)\) which can be installed in the system, \( N_{ems} \): Number of energy storage modules , \( SOC \): State of charge of ESS, \( V_{tr_{reg}} \): Voltage of train at pantograph in regenerative mode, \( V_{reg\_max} \): Maximum regenerative voltage, \( V_{ess\_dis} \): Voltage at ESS terminal in discharging mode, \( V_{ess\_char} \): Voltage at ESS terminal in charging mode, \( w \): weighting factor.

### 2.3 Solving Algorithm

Genetic Algorithm (GA) is selected for problem solving including the complicated constraints and it provides the flexibility for expanding variable size \(^{(3)}\). The basic algorithm of GA is shown in Fig. 3(a). To solve the proposed design problem, the chromosomes are defined as running times, dwell times and energy capacity of ESS. The calculation of fitness function shown in Fig. 3(b) is based on the result of power flow calculation of each time step over a specified period. The terminating criteria is the stall generation satisfying the tolerance of fitness function allowing the algorithm stops when the average relative change in the fitness function value over a predetermined number of stall generation limit.

### 2.4 Estimation of Energy

Estimation of relevant energy is based on the following assumptions.

- For train movement calculation, efficiencies of motor and relevant systems are assumed as constant values.
- Tractive and brake effort’s curve, gradient, curvature, and speed limit are included in the calculation.
- For power flow calculation, resistance per length of running rail and catenary is assumed as constant at a specific temperature.
- For calculating fitness function, the effect of pantograph voltage on tractive 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 supplied from substations will be 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 on train performance. By assuming 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 all substations, the power flow calculation implemented based on the algorithm proposed by (30)-(31) is applied. To determine nodal voltage and current at any point in the system, the power flow calculation considers the exchange of 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. The amount of power in charging mode or discharging mode will be determined based on nodal voltage and State of Charge (SOC) of ESS (29)(32).

Basically, the mismatch of initial and final SOC may affect the total energy supplied especially in cases of ESS having considerable energy capacity. The proposed problem deals with the small energy capacity of ESS and simple energy management scheme. Therefore, sustaining equal SOC at the initial and final state is neglected.

2.5 Evaluation of Regenerative usage and Energy-saving Performance Evaluation of relevant energy is based on a numerical integration of a power profile in the 1-hour period. The indices for comparing the performance of results are defined as \( \% E_{\text{reg}} \) and \( \% E_{\text{save}} \)

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

\[
\% E_{\text{reg}} = \frac{E_{\text{reg}}}{E_{\text{brake}}} \times 100 \quad \quad (2)
\]

2) Energy-saving performance is defined as the percentage of substation energy which can be decreased compared with substation energy of the nominal operation.

\[
\% E_{\text{save}} = \left( \frac{E_{\text{sub, base}} - E_{\text{sub, case i}}}{E_{\text{sub, base}}} \right) \times 100 \quad \quad (3)
\]

2.6 The Effect of Pantograph Voltage on Train Performance Basically, the variation of pantograph voltage affects the performance of traction motor by changing the traction effort characteristics which demonstrate the relation of speed and traction force (34). The relationship of traction force characteristics and pantograph voltage are described based on the equation (4) and (5).

\[
v_l = v_{\text{low}} \cdot \frac{V}{V_N} \quad \quad (4)
\]

\[
v_h = v_{\text{high}} \cdot \frac{V}{V_N} \quad \quad (5)
\]

Where, \( v_l \), \( v_h \), \( v_{\text{low}} \) and \( v_{\text{high}} \) are referred to the tractive effort characteristics of the traction motor. \( v_l \) = low corner speed at current pantograph voltage, \( v_h \) = high corner speed at current pantograph voltage, \( v_{\text{low}} \) = low corner speed at nominal pantograph voltage, \( v_{\text{high}} \) = 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, is selected for demonstrating the integrated design case. There are 13 passenger stations along the 13-km-long double track and seven traction substations shown in Fig. 4. The system parameters for calculation are shown in Table 1.

3.2 Nominal Operating Condition The nominal operation is defined as the operation of 5% time reserve mode or 1.05 of minimum running time. The nominal operating conditions and evaluation of relevant energy are shown in Table 2 and Table 3, respectively. The operating diagram (OD) are shown in Fig. 6. The nominal speed profiles are shown in Fig. 7.

3.3 Preparing Database of Speed and Power Profile Based on the different running times in each section shown in Table 3, the profile for all possible running time in the specified range will be calculated and kept in the profile database for use in the optimization process. The variables for calculating the profile are the following:

- All possible running times in a feasible boundary (in decimal value)
- All operating sections along the route (12 sections)
- Different passenger loads due to traffic conditions (2 conditions, constant for each condition)
- Different running directions (2 directions, southbound and westbound)

Examples of speed and power profiles are shown in Fig. 5.
Table 2. Estimated energy for nominal operation without onboard energy storage

<table>
<thead>
<tr>
<th>Traffic condition</th>
<th>Headway (sec)</th>
<th>Dwell time</th>
<th>Journey time (sec)</th>
<th>Payload (tons)</th>
<th>$E_{peak}$ (kWh/hr)</th>
<th>$E_{avg}$ (kWh/hr)</th>
<th>$E_{max}$ (kWh/hr)</th>
<th>$E_{min}$ (kWh/hr)</th>
<th>%$E_{equiv}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak</td>
<td>180</td>
<td>30</td>
<td>1238/1343</td>
<td>75</td>
<td>10979.25</td>
<td>9462.42</td>
<td>2848.15</td>
<td>3106.55</td>
<td>91.68</td>
</tr>
<tr>
<td>Off-peak</td>
<td>300</td>
<td>20</td>
<td>1184/1188</td>
<td>38</td>
<td>6106.38</td>
<td>5703.20</td>
<td>1028.59</td>
<td>1547.38</td>
<td>66.87</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Traffic</th>
<th>W1</th>
<th>CEN</th>
<th>S01</th>
<th>S02</th>
<th>S03</th>
<th>S05</th>
<th>S06</th>
<th>S07</th>
<th>S08</th>
<th>S09</th>
<th>S10</th>
<th>S11</th>
<th>S12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Hour</td>
<td>Td,min</td>
<td>NA</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Td,max</td>
<td>NA</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Td,nom =&gt;</td>
<td>NA</td>
<td>59</td>
<td>108</td>
<td>101</td>
<td>84</td>
<td>96</td>
<td>69</td>
<td>87</td>
<td>66</td>
<td>76</td>
<td>64</td>
<td>71</td>
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<tr>
<td></td>
<td>Td,min =&gt;</td>
<td>NA</td>
<td>56</td>
<td>103</td>
<td>96</td>
<td>80</td>
<td>91</td>
<td>65</td>
<td>83</td>
<td>63</td>
<td>73</td>
<td>80</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>Td,max =&gt;</td>
<td>NA</td>
<td>62</td>
<td>113</td>
<td>106</td>
<td>88</td>
<td>100</td>
<td>72</td>
<td>91</td>
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<td>80</td>
<td>88</td>
<td>74</td>
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<td></td>
<td>Td,nom &lt;=</td>
<td>61</td>
<td>108</td>
<td>101</td>
<td>84</td>
<td>95</td>
<td>70</td>
<td>88</td>
<td>66</td>
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<td>108</td>
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<tr>
<td></td>
<td>Td,min &lt;=</td>
<td>58</td>
<td>103</td>
<td>96</td>
<td>80</td>
<td>99</td>
<td>67</td>
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<td>67</td>
<td>103</td>
</tr>
<tr>
<td></td>
<td>Td,max &lt;=</td>
<td>64</td>
<td>113</td>
<td>106</td>
<td>88</td>
<td>99</td>
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<td>92</td>
<td>69</td>
<td>88</td>
<td>74</td>
<td>113</td>
<td></td>
</tr>
<tr>
<td>Off-Peak Hour</td>
<td>Td,min</td>
<td>NA</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Td,nom =&gt;</td>
<td>NA</td>
<td>57</td>
<td>106</td>
<td>97</td>
<td>81</td>
<td>95</td>
<td>64</td>
<td>83</td>
<td>62</td>
<td>72</td>
<td>79</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>Td,min =&gt;</td>
<td>NA</td>
<td>54</td>
<td>101</td>
<td>92</td>
<td>77</td>
<td>88</td>
<td>61</td>
<td>79</td>
<td>59</td>
<td>69</td>
<td>76</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>Td,max =&gt;</td>
<td>NA</td>
<td>59</td>
<td>111</td>
<td>102</td>
<td>85</td>
<td>97</td>
<td>67</td>
<td>87</td>
<td>65</td>
<td>76</td>
<td>83</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>Td,nom &lt;=</td>
<td>58</td>
<td>106</td>
<td>98</td>
<td>81</td>
<td>93</td>
<td>65</td>
<td>83</td>
<td>62</td>
<td>72</td>
<td>79</td>
<td>67</td>
<td>104</td>
</tr>
<tr>
<td></td>
<td>Td,min &lt;=</td>
<td>55</td>
<td>101</td>
<td>93</td>
<td>77</td>
<td>88</td>
<td>62</td>
<td>79</td>
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<td>76</td>
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<td>99</td>
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<tr>
<td></td>
<td>Td,max &lt;=</td>
<td>61</td>
<td>111</td>
<td>102</td>
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<td>65</td>
<td>76</td>
<td>83</td>
<td>70</td>
<td>109</td>
</tr>
</tbody>
</table>

In the case study, the energy-saving speed profile has not been considered yet because the proposed design mainly focuses on scheduling and ESS and the distance between adjacent stations is quite short. Therefore, the control objective is focused only on keeping designed running time based on simple train control consisting of three different control input commands, i.e., powering mode with maximum acceleration, coasting, and braking mode with maximum deceleration.

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 wayside ESS is an electrical double layer capacitor module with 1 kWh, 650 kW (33). Parameters of GA are as follows: Maximum number of generations is 500, population is 100 times the number of variables, mutation rate is 0.8, and crossover rate is 0.2. Number of stall generation is 30 with 1e-6 of fitness function tolerance. The numerical cases are performed by using MATLAB on a quad-core, intel core i7-4790, 3.6 GHz with 24 GB RAM.
Table 4. The designed results and evaluation of %E_{save} and %E_{reg} of all case studies

<table>
<thead>
<tr>
<th>Case no.</th>
<th>w</th>
<th>OD</th>
<th>L_{ess} (m)</th>
<th>E_{max} (kWh)</th>
<th>Without Vpant's effect</th>
<th>With Vpant's effect</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>%E_{save} %E_{reg}</td>
<td>%E_{save} %E_{reg}</td>
</tr>
<tr>
<td>Peak hour</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.1</td>
<td>OD1</td>
<td>5696</td>
<td>1</td>
<td>2.34 93.73 2.28 94.78</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.2</td>
<td>OD2</td>
<td>2656</td>
<td>1</td>
<td>4.12 94.53 4.09 96.13</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.3</td>
<td>OD3</td>
<td>8374</td>
<td>1</td>
<td>4.51 94.82 3.55 95.73</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.4</td>
<td>OD4</td>
<td>5731</td>
<td>1</td>
<td>4.64 94.96 3.60 95.73</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.5</td>
<td>OD5</td>
<td>3221</td>
<td>2</td>
<td>5.04 95.45 5.11 96.26</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.6</td>
<td>OD6</td>
<td>3300</td>
<td>2</td>
<td>6.04 96.68 5.47 96.84</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.7</td>
<td>OD7</td>
<td>8191</td>
<td>2</td>
<td>6.41 97.06 6.90 97.15</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.8</td>
<td>OD8</td>
<td>8068</td>
<td>3</td>
<td>6.67 97.43 7.23 97.43</td>
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</tr>
<tr>
<td>9</td>
<td>0.9</td>
<td>OD9</td>
<td>8561</td>
<td>3</td>
<td>7.11 97.94 7.23 97.76</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>OD1</td>
<td>1519</td>
<td>2</td>
<td>3.31 69.10 3.05 64.58</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>0.2</td>
<td>OD11</td>
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Off-peak hour

Variation in weighting factor from a low value to a high value is used to discover multiple solutions for illustrating a Pareto curve to decide the final solution under the operator’s requirements. Moreover, the solutions with different weighting factor demonstrate different design scenarios from cheap infrastructure design to expensive infrastructure design. The designed schedule (OD1-OD18), the location of ESS (L_{ess}) and capacity of ESS (E_{ess}) obtained from the proposed design are shown in Table 4. Based on the proposed design results, the evaluation of %E_{save} and %E_{reg} with and without the effect of pantograph voltage has been performed and shown in Table 4. The timetable parameters for designed schedule are shown in appendix (app. Tables 1 and 2).

From the Table 4, the data in the column mentioned “Without Vpant’s effect” means the calculation of energy is based on the power profile generated from the designed timetable and ESS neglecting the pantograph voltage’s effect on the tractive effort. In other word, the power profiles and voltage profiles are calculated separately. The column labelled “With Vpant’s effect” means the calculation of energy is based on the power profile generated from the designed timetable and ESS and the pantograph voltage’s effect on the tractive effort is considered. The relationship between the pantograph voltage and tractive effort is shown in section 2.6.

The results in Table 4 showed that, for peak hour conditions, when the weighting factor is varied from 0.1 to 0.9, nine different scheduling (OD) and installing scenarios of ESS are obtained. Because the resolution for varying capacity of ESS is 1 kWh, the solutions with the same capacity of ESS can be found. If we consider that additional infrastructure costs are directly related to only the capacity of ESS, the designed results may be classified as cheap infrastructure design, moderate design, and expensive design. From the evaluated results, without the effect of pantograph voltage shown in Table 4, 4.64% of supplied energy can be saved with the cheapest design (i.e., case 4 with OD4 and one module of ESS), and up to 7.11% of energy can be saved with the expensive design (i.e., case 9 with OD9 and three modules of ESS).

For off-peak hour conditions, the results have been obtained in a similar way to the peak hour case. From the results, 4.19% of supplied energy can be saved with the cheapest design, (i.e. case 11 with OD11 and two modules of ESS),
and up to 10.35% of energy can be saved with the expensive design, (i.e., case 18 with OD18 and 4 modules of ESS).

From the numerical results with varying weighting factor, the pareto front based on the multi-objective optimization can be plotted as shown in Fig. 8. With the plot of the pareto curve, the relationship between two objective function is obviously obtained and may be useful in the section of suitable design results under the conditions decided by the operator.

The sensitivity of %E\text{save} to the change of weighting factor is shown in Fig. 9. For both traffic conditions, %E\text{save} there tends to be an increase in the same trend when the weighting factor is increased. However, the increment of %E\text{save} from the lowest to the highest weighting factor shows that the operating performance can be better improved in off-peak conditions. “Cheap design” represents the design scenario with a low cost of investment which requires a small capacity ESS but provides less energy-saving performance. “Expensive design” represents the design scenario with a high cost due to the requirement of large capacity ESS and provides good energy-saving performance. The variation of the weighting factor from low values to large values represents the design scenarios to be ranging from cheap to expansive cases.

As shown in Fig. 10, the location for ESS installation, all cases have a different location and the red circle indicates the recommended location. For peak hour conditions, if we select the location based on the cheap design purpose (low energy-saving performance), the location at TS2 or near S02 would be most suitable for installing ESS because three of the design cases suggest nearly the same location. If we select the location based on the effective energy-saving performance (expensive design), the most suitable location is indicated at TS4 or near S08 because three of the design cases suggest nearly the same location. For the off-peak hour conditions, the location for cheap design tends to be at TS2 or between S01 and S02, while the effective energy-saving location tends to be at TS4 or TS5 or between S07 and S09. Finally, the only suitable location which satisfies the designer’s requirement will be decided. Therefore, the suitable location based on the case studies is recommended as the following. The suitable location based on cost-saving purposes which is effective for both traffic condition tends to be at TS2 or between S01 and S02. The suitable location based on energy-saving purposes which is effective for both traffic condition tends to be at TS4 or between S07 and S09.

The deviation of %E\text{save} and %E\text{reg} shown in Fig. 12 results from the deviation in running time shown in Fig. 11. When the effect of pantograph voltage is included in calculation, the running time in some sections deviates from the designed running time. Due to the deviation, the synchronization of train scheduling tends to be degraded. In this case study, the journey time with slight deviation is obtained less than 12 seconds or only 1% of total designed journey time. %E\text{save} and %E\text{reg} shown in Fig. 12 are slightly degraded with the maximum decrement of 3% and 5% respectively. The effect of pantograph voltage affects both the %E\text{save} and %E\text{reg}. In peak hour conditions, the increment and decrement of the %E\text{save} and %E\text{reg} can be found, but in the off-peak conditions considerable decrement of the %E\text{save} and %E\text{reg} was
Efficient Urban Railway Design Integrating Train Scheduling, Wayside (Warayut Kampeerawat et al.)

Fig. 11. Deviations or errors in the total designed journey time due to the effect of pantograph voltage

Fig. 12. %E_{save} and %E_{reg} VS E_{ess} with and without effect of pantograph voltage

Fig. 13. Peak power reduction and voltage regulation

observed. Because the control of wayside ESS is related to voltage, the effect of voltage entails some considerable change in evaluated performance for both traffic conditions. The reduction of energy-saving performance may result from the loss of synchronization of designed scheduling due to the deviation in running time in some sections. However, if the operator wants to keep the journey time as the designed journey time, the speed profiles of the sections suffering the deviation in running time can be compensated for by considering the compensation of the effect of pantograph voltage.
Even though the reduction of peak power and voltage regulation at power substations are not considered as the design objectives, the considerable reduction of peak power can be observed. From Fig. 13(a), the considerable reduction of approximately 40% in peak power was seen at substation no. 2 in peak hour conditions, and the considerable reduction of approximately 40% at substation no. 3 in off-peak hour conditions. When the peak power is reduced, the voltage drop at the substation is also improved. As shown in Fig. 13(b), the minimum voltage at substation no. 2 and 3 is obviously improved compared with the nominal condition in peak hour conditions.

To compare the effectiveness of the designed scheduling with that of the nominal one, the performance of the designed scheduling and those of the nominal scheduling are compared by means of \( \%E_{\text{save}} \). Case 4 and 11 are the cheap design case in peak hour and off-peak hour, respectively. Case 9 and 18 are the expensive design cases in peak hour and off-peak hour, respectively. The designed case (i.e. case 4, 9, 11, 18) means both the designed ESS and the designed scheduling are applied, while the modified case (i.e. case 4*, 9*, 11* and 18*) means the designed ESS is applied but the nominal scheduling is used instead of the designed scheduling. The \( \%E_{\text{save}} \) shown in Fig. 14 shows that the designed scheduling is always more effective than the nominal one. In the case of the cheap design or low-energy-saving cases \( \%E_{\text{save}} \), the designed scheduling can provide up to 0.7% better \( \%E_{\text{save}} \). In the case of the expensive design or efficient energy-saving case \( \%E_{\text{save}} \), the designed scheduling can provide up to 1.3% better \( \%E_{\text{save}} \).

4. Discussions

4.1 Determining Optimal Capacity and Location of ESS By performing multiple case studies with different weighting factors, the Pareto front can be a useful provider of information in deciding on suitable solutions under operator’s requirements. The variation of weighting factor represents the level of energy-saving performance required by the operator. The large weighting factor provides high energy-saving performance with expensive infrastructure design, while the small weighting factor tends to reduce the cost of infrastructure. From the case study, the capacity of ESS varies with a large step. Therefore, the design scenarios may be simply classified as a few scenarios based on the designed capacity of ESS, i.e. cheap infrastructure design, moderate infrastructure design, and expensive infrastructure design.

With the different capacities of ESS, various solutions of location may be obtained. To decide the suitable location for installing ESS, the suggested locations from the design results are to be considered with other conditions. If the suggested location is not feasible or the suitable location is to be fixed by the designer, then the proposed design can be performed with a fixed location of ESS.

4.2 The Effect of Pantograph Voltage Because the ESS control scheme is based on nodal voltage, the variation of pantograph voltage does not affect the performance of the traction system nor the operation of ESS. Disregarding the voltage effect in the design process can simplify the calculation while the variation of designed results and performance can be obtained. Looking at the comparison between the numerical results with and without the effect of voltage, the variation of voltage in an acceptable range entails small deviation in the designed scheduling that may degrade the energy-saving performance, especially in case of off-peak hour conditions. Therefore, small deviation in some running sections may be allowed if the design scheduling and speed profiles are applied to the system operation without any modification.

4.3 Peak Power Reduction and Voltage Regulation The proposed design mainly focuses on the energy-saving issue, but a further advantage of the wayside ESS is that it still enables the power peak reduction and voltage regulation, especially in peak hour condition when the high peak power can be reduced considerably at some substations and the voltage regulation can be also improved.

4.4 Concerns Regarding an Application of the Proposed Method The design operating condition aims to improve energy-saving operation with non-redundant capacity of ESS installed at an effective location. Because the scheduling parameters and ESS parameters are optimized simultaneously by a heuristic method, the proposed design is quite a time-consuming process. The proposed design is supposed to be used in the design or planning phase based on simplified assumptions.

The proposed design is supposed to optimize the timetable and ESS’s scheme for only one traffic condition selected by the designer. Considering two or more traffic conditions may make it difficult to obtain one effective timetable for all traffic conditions. The recommended traffic condition may be the off-peak hour which has a higher possibility of improving regenerative power usage and a longer operating period. Therefore, the effectiveness of the designed timetable may be degraded in other traffic conditions. Performing the design under different traffic conditions may be useful in deciding the final design scenario. From the case studies, the different traffic conditions require different timetables and ESS capacity. Obviously, the optimal installed scenario of ESS (location and capacity) will be decided and cannot be changed, but the timetable can be fixed or adjusted to suit the traffic conditions.

Moreover, in practical operation, the variation of pantograph voltage can degrade the performance of designed operating conditions. Without compensation for the deviation due to the effect of voltage, the operation improvement is impractical.
still considerable when looking at the numerical evaluation of case studies. The compensation of the effect of pantograph voltage may be considered in future work.

5. Conclusions

This paper presents a simultaneous design of train scheduling and installation scenarios of wayside energy storage. The main objective is to integrate the design of train operation, infrastructure, and traction power management schemes to enhance energy-saving operation and the flexibility of energy management. The designed solution is based on minimizing energy supplied from substations and the energy capacity of ESS. The objective function is developed to combined energy-saving purpose and cost-saving purpose by varying weighting factor. To demonstrate the performance and concerns on the proposed design, the numerical case studies have been performed on the urban railway operated in Thailand. The design timetable parameters and appropriate installation scenarios of ESS (i.e. capacity and location) obtained from the proposed design can provide an improvement of energy-saving operation and the flexibility of energy management.

The proposed design excludes the effect of voltage from the optimization process to simplify the problem. Therefore, the performance of design operation may be degraded by the variation of pantograph voltage in practical operation. From the comparison, the variation of voltage entails some small errors in the design scheduling and degrades the energy-saving performance, especially in off-peak hour conditions. That being said, small deviations in some running sections are allowed in the operation without any modification of designed condition. The improvement of energy-saving performance is still obtained.

For future work, the compensation on the effect of pantograph voltage will be considered. In addition, the effect of traffic variation on the performance of design scheduling will be considered and discussed.

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Appendix

app. Table 1. Designed operating timetable (Peak hour)

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Warayut Kampeerawat (Student Member) received the B.S. degree and the M.S. degree in electrical engineering from Khon Kaen University, Khon Kaen, Thailand, in 2005 and 2007, respectively. He is currently pursuing a Ph.D. in the Department of Electrical Engineering and Information Systems, Graduate School of Engineering, The University of Tokyo. He is a lecturer in the Department of Electrical Engineering, Faculty of Engineering, Khon Kaen University, Thailand. His research fields include applying optimization techniques to power system and railway system design.

Takafumi Koseki (Member) received his Ph.D. in electrical engineering from The University of Tokyo, Tokyo, Japan, in 1992. He is currently a Professor in the Department of Electrical Engineering and Information Systems, School of Engineering, The University of Tokyo. His current research interests include applications of electrical engineering to public transport systems, linear drives, and control of traction system. Dr. Koseki is a member of the Institute of Electrical Engineers of Japan, Japan Society of Mechanical Engineering, the Japan Society of Applied Electronics and Mechanics, Japan Society for Precision Engineering, and Japan Railway Electrical Engineering Association.