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Evaluation of mobile and stationary applications of energy storage for DC railways and rapid transit

Ivan Grigorchenkov, Dr David Johnson, Professor Keith Pullen,
City University London, School of Engineering and Mathematical Sciences

Abstract – **A meaningful comparison of stationary and mobile applications of energy storage on DC railways requires assessment of their values with respect to strategic objectives rather than merely energy savings. This paper describes a possible treatment of the problem and outlines an evaluation process for determining the preferred alternative on the whole-life cycle basis. A multiple-objective approach to the evaluation can compliment commonly used cost-benefit analysis and help decision makers in effective integration and deployment of energy storage technology on DC railways and rapid transit.**

Keywords – **comparison, energy storage, evaluation, mobile, stationary**

I. INTRODUCTION

EMERGING energy storage technologies offer a range of benefits to electric railways across areas of economic, environmental and operational challenges. Energy storage devices (ESD) have already demonstrated in trials [1] reductions in traction electricity consumption and associated CO_2 emissions as well as increases in the current-carrying capacity of the electric power supply system, improved voltage levels, potential savings on infrastructure investments, and advantages for passengers such as reduced journey time and improved thermal conditions in subterranean railways. There are also some other benefits of the technology in a wider context of the electricity regulation market [2] and integration with an electric vehicle infrastructure [3].

However, the overall impact depends on the type of energy storage used, its energy and power characteristics, and its physical location. At present, most suitable energy storage devices for DC railways are some types of batteries, electric double-layer capacitors, and electromechanical flywheels.

The ESDs can be installed on trains or alongside the tracks, or in combination. The fundamental difference between stationary and mobile installations lies in power flows; a train equipped with energy storage draws less power from the electric power supply system than a train operating on a route with track-side energy storage under equal operational conditions. The difference in power flows affects electric currents, voltage levels and other related properties of the system such as vehicle acceleration rates, power losses, and thermal loads on traction equipment, etc.

The problem of selection between alternative installations involves contradictory objectives. For instance, train-borne energy storage provides some additional gains compared to track-side installation although it increases the overall weight of the vehicle. This, in turn, may have negative effects on track wear and train resistance to motion unless other components can be reduced in size in conjunction with the ESD installation.

In order to determine the preferred alternative, it is necessary to evaluate trade-offs of the installations on the basis of the whole-life cycle taking into consideration strategic objectives. Energy savings are often used as a single criterion for assessment of energy storage effectiveness, sizing and optimal location [4, 5]. This approach neglects certain aspects and may potentially lead to unacceptable results with respect to other important goals. A more meaningful comparison of stationary and mobile applications requires assessment of their values with respect to multiple objectives rather than merely energy savings.

A multiple-objective approach to the evaluation problem can compliment commonly used cost-benefit analysis and help decision makers in effective integration and deployment of energy storage on DC railways.

II. DECISION CONTEXT

Stationary and mobile ESDs can contribute to strategic objectives in different ways. Some of the possible impacts in the context of the four key challenges for UK railways, known as the “4Cs”, are shown in Table 1.

Many of the benefits of energy storage can be quantified and used for selecting the preferred type of installation. Value judgement also includes capital expenditure on the equipment, operating and recycling costs as well as some undesirable implications of the technology, such as:

- Possible track wear due to extra weight of a train-borne energy storage;
- Land use of stationary ESDs;
- Safety;
- Interoperability.

The required capacity and number of ESD units to deliver a comparable value can differ widely for track-side and on-board installations; variables include the number of vehicles operating on a route, frequency of stops and the configuration of the electric power supply system.

For a given system configuration and route topology a feasible set of possible installations is determined by some requirements, constraints and the following controllable design variables:

- Power rating of a ESD unit, kW;
- Usable energy of a ESD unit, kWh;
- Energy management strategy;
- Number of units;
- Physical location.

The difficulty of evaluation of alternative installations originates from the presence of a number of factors:

1. *Multiple quantitative and qualitative criteria;*

   Multiple criteria add computational complexity to selection and finding the optimal size and location of energy storage. Some of the criteria can be expressed in qualitative terms only. For instance, catenary-free operations improves aesthetic look of electric railways in historical parts of cities (in addition to savings on infrastructure).

2. *Conflicting preferences of stakeholder groups;*

   Individual preferences and priorities of stakeholders have to be taken into account during the evaluation process.

3. *Randomness associated with railway operations;*

   Variations in traffic and passenger loads are inherent in railway operations. These factors have considerable effect on the performance of regenerative braking, and, hence, energy storage requirements. In addition, driving styles, train formations and weather conditions also affect energy regeneration rates.

4. *Imperfection of data;*

   The performance of alternative installations is subject to uncertainty of system parameters, such as future variations in traffic and passenger loads, as well as the values associated with the 4Cs strategic objectives. For example, current-carrying capacity may not be a problem at the time when evaluation is undertaken. However, introduction of more powerful rolling stock in future might require additional current-carrying capacity to accommodate new trains on the route.

5. *Variations in routes' topology across network, and rolling stock characteristics.*

   Railway vehicles often operate on different routes over their life-time, and energy storage requirements may vary from one route to another.

To make a meaningful comparison it is necessary to evaluate performance of alternative installations under equal operational conditions for a specific railway line or a synthetic reference route [6]. Both stationary and mobile installations have to be optimised with respect to their contributions to the strategic objectives.

III. CRITERIA

Multi-objective formulation of the evaluation problem requires measuring the degree to which fundamental objectives are achieved by some quantitative and qualitative criteria.

TABLE I

EXPECTED 4CS IMPACTS OF ENERGY STORAGE

1. **C**ustomer.
   1.1. Reduced journey time.
   1.2. Improved thermal conditions in subterranean railways.
   1.3. Reduced delays due to electric power supply disturbances.
2. **C**apacity.
   2.1. Increase in electric current-carrying capacity.
   2.2. Higher vehicle acceleration rates.
3. **C**ost.
   3.1. Reduced electricity consumption.
      3.1.1. Traction electricity.
      3.1.2. Power losses in the current conductor and electric insulators.
      3.1.3. Substation losses.
      3.1.4. HVAC energy consumption.
   3.2. Reduced peak power demand.
   3.3. Better utilisation of electrification assets.
      3.3.1. Lower equipment power rating.
      3.3.2. Reliability and life expectancy of transformer, rectifier, traction motors and current collection equipment.
      3.3.3. Smaller cross section of the electric current conductor.
      3.3.4. Simplified stray currents protection.
      3.3.5. Increased spacing between power substations.
      3.3.6. Gradual transition to discontinuous electrification.
   3.4. Minimised costs of thermal conditioning of underground stations.
   3.5. Minimised service delays.
      3.5.1. Power supply interruptions.
      3.5.2. Improved reliability of equipment.
4. **C**arbon – improved environmental performance.
   4.1. CO_2 emissions.
   4.1. Electromagnetic emissions of the current collection.
   4.3. Particle emissions.

TABLE II

BASIC CRITERIA

1. Energy consumption.
   1.1. Total traction electricity consumption.
   1.2. Peak demand coefficient.
   1.3. Power loss in the current conductor and electric insulators.
   1.4. Power loss in traction motors.
   1.5. Power loss at substation.
   1.6. Power loss in braking rheostats.
2. Electric currents.
   2.1. Effective current of a substation.
   2.2. Effective current of a feeder.
   2.3. Effective current of a train.
3. Voltage levels.
   3.1. Mean useful voltage at the current collector.
   3.2. Mean useful voltage at the substation busbar.

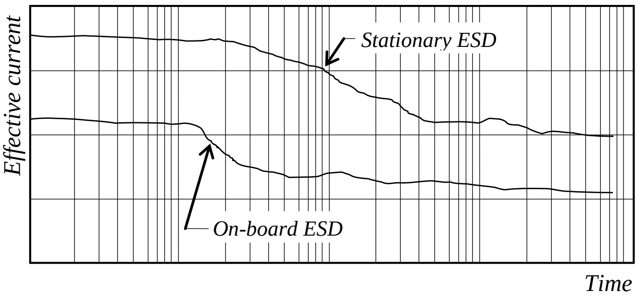

Fig 1. Time-weighted equivalent continuous load curves for effective currents of a power substation feeder.

In many cases the impact of energy storage has a direct correlation with the physical properties of the system in terms of electrical work, current, voltage and time. For instance, CO_2 emissions are proportional to the overall energy consumption; Train acceleration rates depend on voltage levels on the current collector; Ageing of power transformers depends on thermal loads on the insulation caused by electric currents.

Electricity consumption, currents and voltages are practical measures for the purpose of energy storage evaluation; they are the basic criteria that can be calculated by means of numerical simulations. Some examples of the relevant quantities are given in Table 2. The number of criteria depends on particulars of a specific case.

The basic criteria of electrical work, currents and voltages should reflect the time-dependent nature of the quantities. Therefore, it is necessary to determine their equivalent time-weighted values and coefficients describing their variations over time. An illustrative example of time-weighted equivalent load curves is shown in Figure 1.

Other criteria, or attributes, for energy storage evaluation, such as, safety, interoperability, and track wear or land use, have no direct correlation with the physical quantities mentioned above, although they should also be included in the evaluation process.

The advantage of having these two separate sets of criteria is that evaluation of energy storage can be conducted in two stages, as shown in Figure 2.

At first, non-dominant sets of feasible designs for both types of installations are obtained by optimisation with respect to the basic criteria with a posterior articulation of preferences. It is necessary to determine the Pareto optimal sets or representative subsets for track-side and on-board ESDs.

During the second stage, a multiple-criteria analysis must be undertaken to determine the preferred type of installation. There are various techniques and methods available for this class of problems [9]. For instance, multiple-attribute utility theory can be applied to the problem. The preference model should include previously obtained Pareto fronts and utility functions reflecting a decision-maker’s preferences and uncertainty associated with values of the fundamental objectives.

IV. EVALUATION OF ENERGY STORAGE APPLICATIONS

A meaningful comparison of alternative installations requires assessment of their performance with respect to the fundamental objectives under equal operational conditions. The comparison should be made between optimal designs. The general evaluation procedure is illustrated in Figure 2 and described below.

Specification of operational parameters

There are a number of parameters that have to be identical for both stationary and mobile installations during the evaluation process. This includes timetable, route topology, configuration of the electric power supply system, number and location of stops and passenger loads. Numerical simulations allow computation of energy consumption, electric currents and voltages on a specific route for all possible alternative installations.

Parameters affecting the physical quantities may vary considerably from one route to another. In the case where energy storage is to be deployed across a railway network, it is practical to equalise the route parameters in order to obtain a single equivalent route. The concept of a synthetic route can be used for this purpose [6]. This approach is intended to eliminate “minor variation that detracts from essentials of energy equivalence”.

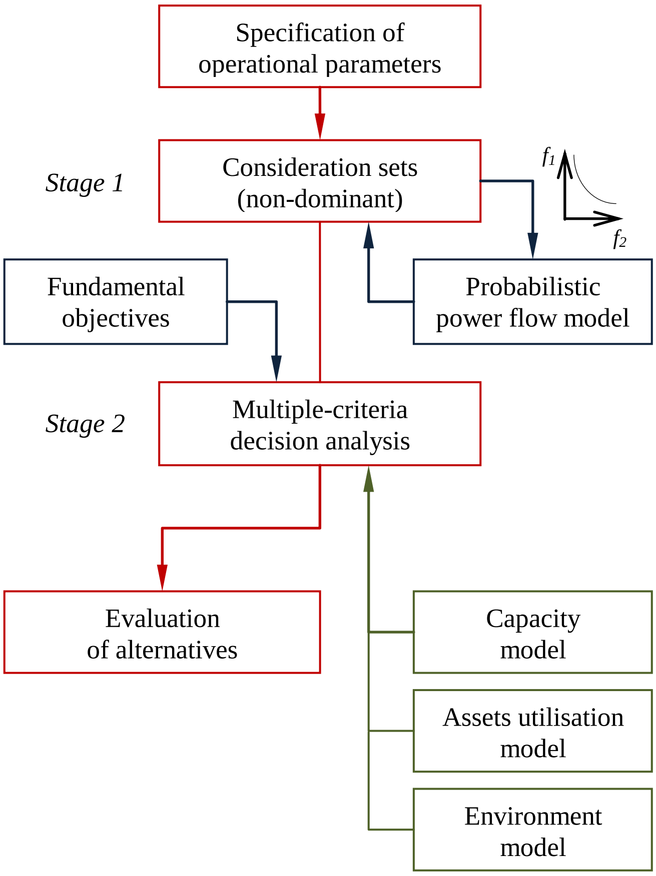

Fig 2. Evaluation process

Consideration sets

Solutions that are feasible are determined by the design variables and a number of constraints. The consideration sets are made up of those feasible designs that satisfy objectives without being dominated by one over another.

In order to determine the consideration set for a specific type of energy storage installation, it is necessary to perform multiple-objectives optimisation with a posterior articulation of preferences. The method of Genetic Algorithms is a popular heuristic approach to solving complex multiple-objective optimisation problems with non-convex and discontinuous solution spaces. The objective function can be formulated, for example, to minimise energy storage capacity, effective current of substation feeder, the overall energy consumption, and to maximise the mean useful voltage at the current collector to the nominal level.

While many optimisation problems are deterministic, it is vital to recognise the randomness associated with railway operations [7]. Performance of regenerative braking incorporating energy storage depends on a range of factors: daily, monthly and annual variations in traffic density and passenger loads; driving styles and train formations; weather conditions, etc.

Monte Carlo simulation is a suitable method to address variability and uncertainty in the optimisation problem [7, 8]. The random quantities can be expressed in terms of probability density functions. For each solution from the genetic algorithm space, the variables mentioned above generated randomly and used for a deterministic simulation run. The procedure is then repeated until sufficient number of random samples is simulated.

It is important to handle constraints strategies effectively to minimise the number of infeasible solutions within the solutions search space.

Multiple-criteria decision analysis

Once the consideration sets are determined for stationary and mobile installations, it is possible to evaluate them with respect to fundamental objectives and select the two preferred solutions of each type.

There is a range of techniques and methods available for preference modelling [9]. Multiple-attribute utility theory has gained broad popularity among researchers and decision-makers over the past two decades. Its methods can handle a wide range of criteria under conditions of conflicting preferences among stakeholder groups, and high uncertainties. The latter is particularly important for energy storage evaluation on the basis of the whole-life cycle, as the life time of some ESDs are comparable to the life time of railway vehicles.

Evaluation of alternatives

Finally, two selected alternative can be compared by their relative utilities.

V. CONCLUDING REMARKS

The comparison of stationary and mobile applications of energy storage applications involves assessment of multiple trade-offs. In this paper an evaluation process of mobile and stationary energy storage with respect to the strategic objectives has been outlined. The proposed approach allows a more meaningful comparison of alternatives and supports effective deployment of energy storage technology on DC railways.

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