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Coordinated Energy Management of the Electric Railway Traction System: Croatian Railways Case Study

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Abstract

A railway energy management system based on hierarchical coordination of electric traction substation energy flows and on-route trains energy consumption is presented in the paper. The railway system is divided into energy-efficient individual trains energy consumption management as a lower level, and the energy-cost-efficient electric traction substation energy flows management as a higher level. The levels are coordinated through parametric hierarchical model predictive control with the main goal of additionally decreasing the operational costs of the overall system. Through interactions with the power grid at the higher level, the system can provide ancillary services and respond to various grid requests. At the same time, lower level trains driving profiles are adjusted to attain the minimum cost of system operation with timetables and on-route constraints respected. The developed algorithm is verified against a detailed real case study scenario with the presented results showing significant cost and energy consumption reductions.

Keywords: *train traction energy consumption, electric traction substation energy flows, energy management, hierarchical model predictive control.*

1. Introduction

In order to cope with the rise in transport demand and recent increase of railway activity [1], electric railway traction systems are a promising area for the implementation of advanced energy management strategies with the goal of increasing energy efficiency and reduction of CO_2 emissions (emphasized in the European Union climate and energy targets for 2030 [2]). With the integration of driver advisory systems, advanced energy meters, four-quadrant drives and various energy storage technologies, railway systems are transforming through smart control systems into active participants in the power grid.

A significant research focus of railway system energy efficiency is put on: (i) reducing the energy consumption of an individual train as in [3] and, more recently, on (ii) better utilization of regenerative braking energy, either by timetables optimization [4], or by introduction and implementation of different energy storage systems [5]. Energy-efficient train driving methods minimize energy consumption during train travel between adjacent stations while respecting the timetables, on-route restrictions (speed limits, train traction force boundaries etc.) and passengers' comfort, with savings of up to 30% reported in [4]. Optimization of timetables, so that multiple trains acceleration and braking intervals are synchronized, shows possible energy consumption reductions by up to 29%, with an extensive survey presented in [4]. Combination of multiple energy storage systems (batteries, supercapacitors and flywheels) introduces an additional energy savings potential by up to 30% [5]. Integrated approaches, which jointly optimize the timetable and trains driving profiles, show improved performance since they take into account the minimization of the tractive energy consumption of each train while maximizing the utilization of regenerative energy between multiple trains [6]. The listed railway system energy efficiency approaches exclude the power grid perspective. The focus is instead put solely on the processes and subsystems of the railway system. The possible benefits of railway system active interaction with the future electricity grids show the railway system ability to participate in energy markets, offer ancillary services to the power grid operator [7] and integrate renewable energy sources [8]. However, this is done without considering the optimization of timetables or traction profiles, thus ignoring the significant potential in their rearrangement.

In this paper, the railway system is considered through the coordination of the on-route trains energy consumption level and the electric traction substation (ETS) energy flows management level with the goal of increasing energy efficiency, decreasing operational costs and enabling the integration of railways into smart electricity grids. The algorithm for hierarchical coordination is developed and presented in [9] together with a case studydesigned for the verification of the developed control system within a realistic scenario taken from Croatian Railways.

The paper is organized as follows. Problem definitions at both levels are presented in Section 2 together with the concept of hierarchical coordination between the levels. The realistic case study scenario is described in detail in Section 3 together with the corresponding results presented in Section 4. The conclusions are given in Section 5.

2. Hierarchical model predictive control for coordinated energy management

Optimization problems for both on-route trains energy consumption (lower) and ETS energy flows management (higher) levels are described hereinafter.

Lower hierarchical level

The method for energy consumption minimization of a single train traveling between two stations was initially described in [10, 11] where explicit constrained finite-time optimal control of piecewise affine systems is employed to calculate the optimal traction force control law. The energy-efficient train driving control problem aims at finding the train traction/braking force that minimizes the mechanical energy consumption used for train traction while reaching the next station at the allotted time and continuously respecting all the physical constraints imposed on train speed, traversed path and traction force along the rail path.

Higher hierarchical level

At the higher, energy flows optimization level, the model predictive control (MPC) problem is formulated with a linear cost function for the economically optimal energy flows [9]. A single ETS is observed from the point of balancing energy flows between the accelerating and decelerating trains, the energy storage system and a connection to the utility grid with variable energy prices and various demands from the utility grid operator. Energy flows optimization results in optimal charging/discharging profiles for storage components that guarantee the optimal economic cost on the prediction horizon while taking into account the current state-of-charge of the energy storages, predicted trains consumption profile, volatile electricity price profile representing the economic criterion of the utility grid, and technical constraints in system components. The HHL problem is reformulated as a multi-parametric MPC problem with the parameters set obtained from the LHL.

Hierarchical coordination for energy management

Hierarchical coordination between the LHL and HHL is performed through revisiting of both control levels with the goal of improving the initial energy-optimal LHL solution for individual trains with respect to the HHL cost for energy exchange, thus transforming it into a global economically optimal solution for the traction substation. The iterative coordination scheme is depicted in Fig. 1, executed until the LHL solution converges

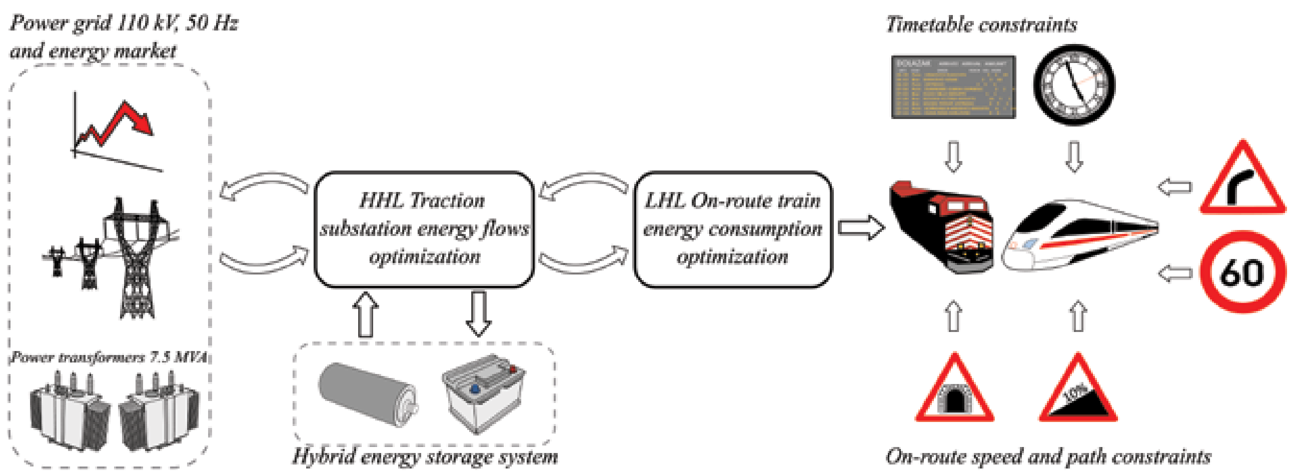

Fig. 1. Scheme and information flow of hierarchical coordination between LHL and HHL optimizations.

with respect to the global criteria under the given constraints, i.e. when the train traction force energy-optimal profile is shifted to the price-optimal profile. A detailed description and mathematical formulation of the hierarchical coordination algorithm is presented in [9].

The modularity and hierarchical structure of the presented algorithm keeps the considered subsystems operation apart since they are often required to remain infrastructurally and technologically independent, but also usually legally separated to infrastructure companies for operating power supply and different transportation companies for operating the trains. Due to the modular structure of the algorithm, the levels are able to operate independently when e.g. the train operation at the lower level cannot be changed. It is also possible to extend the proposed algorithm with new levels, e.g. for the simultaneous coordination of multiple traction substations so that a longer rail segment of the infrastructure operator is considered.

3. Case study simulation scenario

The case study is based on actual trains, time schedules and rail route configurations. The trains time-schedule and rail route configuration are taken from the railway section of Corridor X of Croatian Railways Infrastructure in Slavonia region (eastern Croatia) [12]. A traction segment of ~56 km (between the two neutral sections) supplied from ETS Andrijevci was selected. It includes 10 passenger stations, has small to no track gradient and no curves or tunnels. The considered rail path is depicted in Fig. 2 with the corresponding passenger stations locations. Travel distances and times are presented in [9].

The considered train configuration is the low-floor electromotive train (EMT) for the urban and commuter operation manufactured by Končar - Electric Vehicles Inc. [13]. The EMT is designed as a low-floor four-part train with a total length of 75 m, built for rails electrified with catenary power supply of 25 kV voltage and 50 Hz frequency, with a maximum speed of 160 km/h. The detailed Končar EMT parameters can be found in [9].

The connection to the utility grid is made via two 110/25 kV transformers of 7.5 MVA power each. The transformers have the ability to return energy back to the utility grid (with imposed amount limit set to 1 MW) which offers a possibility for interaction with the power grid and better utilization of excessive regenerative and/or stored energy. The considered hourly varying prices for energy exchange are based on European Power Exchange prices (EPEX [14]), which are available one day ahead.

The energy storage system is modeled as a joint operation of battery energy storage system and a supercapacitor. Selection of the supercapacitor is justified for collecting the regenerative braking energy with large number of charging/discharging cycles, due to its large power density, while battery storage is selected with the aim of collecting larger amounts of energy during longer periods of time, due to the battery high energy density. The considered energy storage system parameters are based on commercially available storage systems listed in [9].

4. Simulation results

Traveling through ETS Andrijevci supply area lasts around 60 minutes (including 1 minute stops in all passenger stations) according to the Croatian Railways timetable for the rail path length of 60.7 km between stations Slobodnica and Ivankovo. The calculated

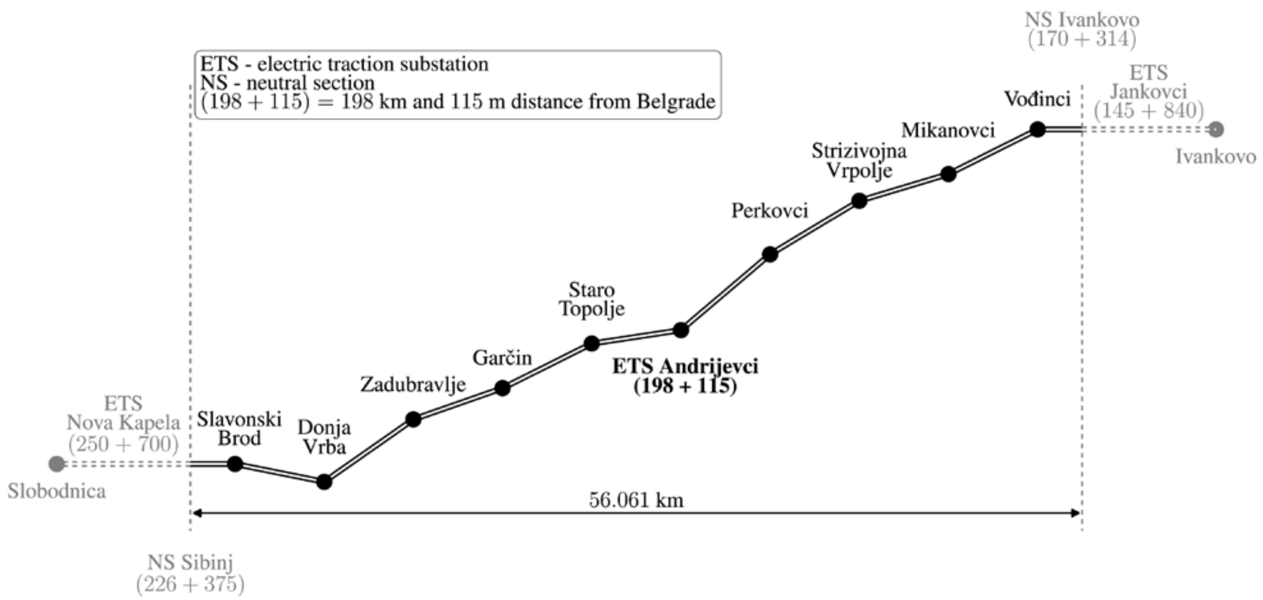

Fig. 2. Croatian Railways Corridor X section area supplied from ETS Andrijevci with the corresponding passenger stations.

energy-optimal train traction force profile is presented in Fig. 3 together with the corresponding travel speed and traversed path profiles.

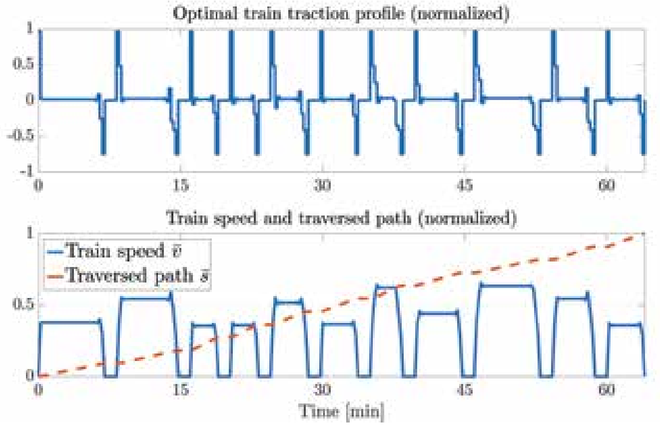

Fig. 3. Energy-optimal train traction force, speed and traversed path profiles while traveling from Slobodnica to Ivankovo.

After the initial results are obtained from the LHL, the energy-optimal train travel consumption profile is created for a train traveling through the ETS Andrijevci supply area. To simulate the Croatian railways timetable for the considered ETS Andrijevci area for one day, the created travel profiles from Fig. 3 are stacked in time with all the passenger trains considered identical.

The HHL control system operation is simulated during a daily system operation according to the Croatian Railways timetable together with volatile EPEX prices and a prediction horizon of 24 h. Simulation scenario results are depicted in Fig 4 and comprise of: (i) energy exchange price profile, (ii) ETS power flows (summed trains energy consumption/production), (iii) energy exchanged with the utility grid and (iv) energy storage state of charge for both energy storage components.

The hierarchical coordination algorithm is simulated for the period between 13:00 and 14:00 with all together 13 trains supplied from ETS Andrijevci at some point during the one-hour period, according to the timetable.

From the results presented in Figures 5 and 6, the following is observed: (i) the coordination between the control levels reduces the amount of energy that is being unused, i.e. dissipated in the resistors (shown with the red line in the first plots of both figures), (ii) the peaks of produced regenerative energy are reduced as the regenerative energy production from a single train is being distributed towards other trains (shown with the

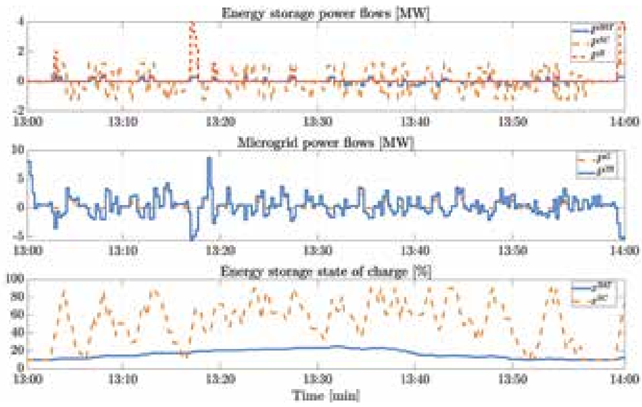

Fig. 5. One-hour system behavior without coordination.

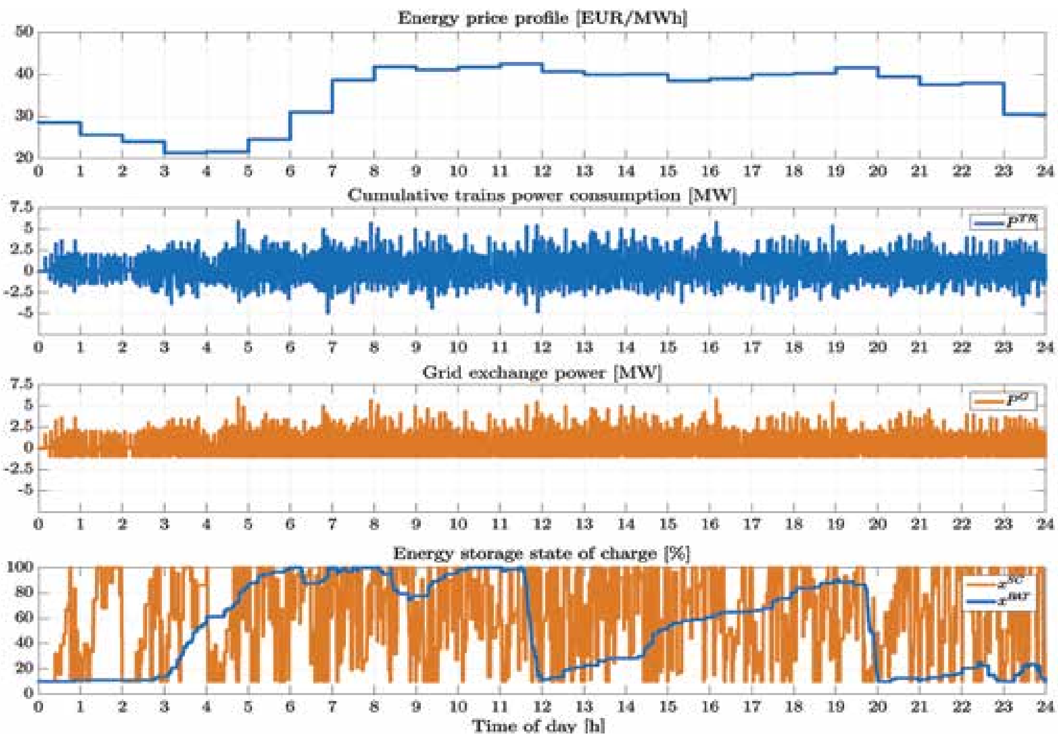

Fig. 4. Daily power flows for system operation with only higher level MPC installed and grid receptiveness of -1 MW

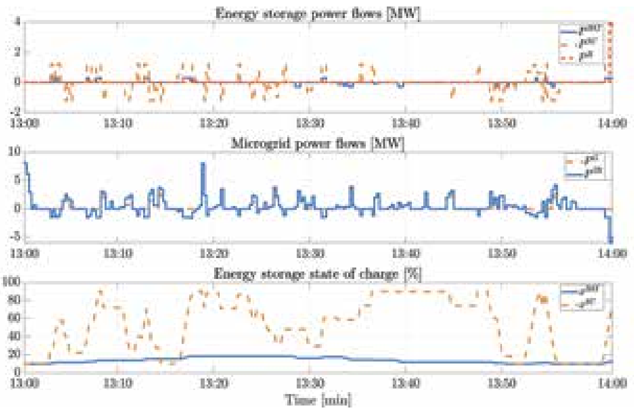

Fig. 6. One-hour system behavior with coordination.

blue lines in the middle plots of both figures) and (iii) the use of the energy storage systems is reduced since their operation causes energy losses due to energy efficiency of the storage technologies (shown with the red and orange lines in the first and last plots of the figures).

The power consumption of individual trains during this one-hour simulation period is presented in Fig. 7, individually for four trains that are supplied during most of the one-hour period from the considered ETS, and cumulatively for the remaining 9 trains. The neighboring trains exchange energy and cooperate in order to reduce system operation costs. Such energy exchange between the trains can be seen when more trains are in braking and therefore generate a large amount of energy that is then consumed by other trains currently supplied from the same ETS, and now deviate from their initial traction profiles in order to consume this energy. Although these trains then operate with a suboptimal traction profile and actually consume more energy, the system benefits from this interaction between trains since most of the regenerative braking energy would be dissipated if the trains would not be coordinated. This behavior can be seen in Fig. 7 where e.g. Train 1 speeds up at 13:03 to consume the energy generated by the remaining trains and reduces the cumulative regenerative energy peak (subplot 5), or where trains 3 and 4 brake early at 13:15 and 13:17, respectively, to shift their consumption profiles and reduce the overall regenerative energy production from 13:17 to 13:18 (subplot 5). Although the traction profiles of the trains change, the schedule is maintained, and operational constraints are respected.

Different variations are introduced to the initial simulation set-up, with corresponding cost and energy consumption reductions compared and the results presented in Fig. 8. Cost and energy reduction quantities in all cases are obtained through comparison with the costs and energy consumption of system operation without the HHL control and with trains driven in the energy-optimal way.

The results obtained via solely MPC applied to a higher level control with energy-optimal traction profiles applied for individual trains, but without coordination, are then compared with the baseline case and the results achieved with coordination. The results obtained show that the energy consumptions reductions reach up to 40%

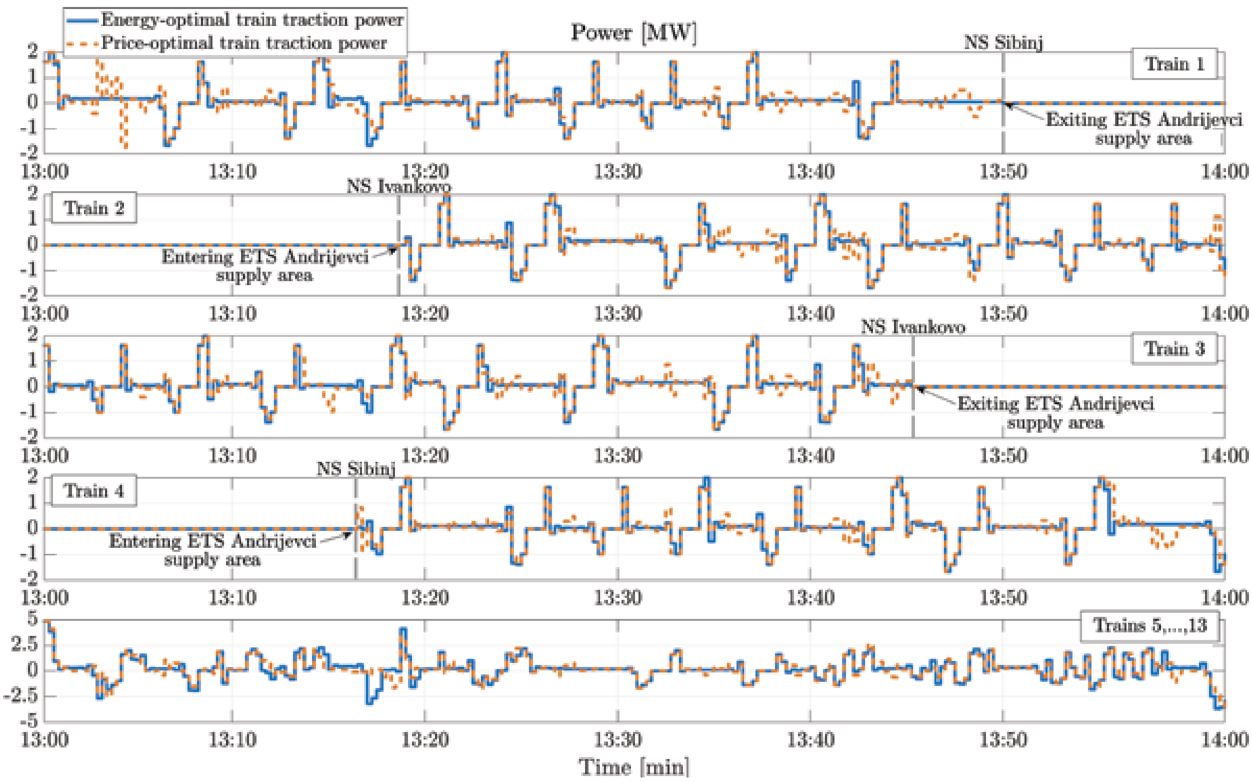

Fig. 7. Power consumption profiles of all trains supplied from ETS Andrijevci, before and after hierarchical coordination, for a one-hour system operation

while the costs are reduced up to 45%, as presented in Fig. 8.

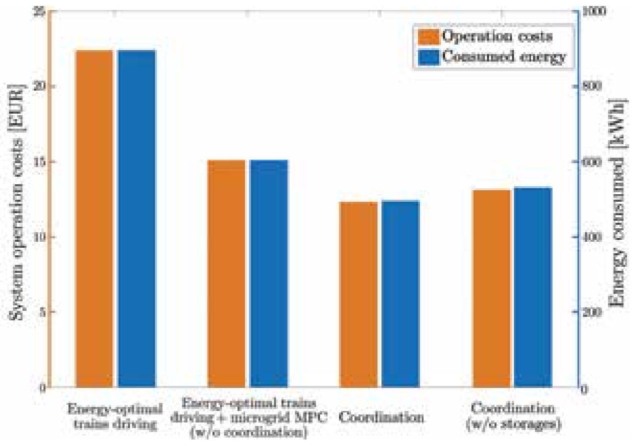

Fig. 8. Energy consumption and system operation costs for different control setups for the one-hour system operation

An additional simulation case was added to the setup, in order to investigate system operation without energy storage systems implemented and with coordination between the levels. From the results presented in Fig. 8 it is observed that the software-based coordination at the lower level can eliminate the need for storages, since the cost reductions are only slightly decreased when no energy storage systems are installed in the system. Although such control system setup does not provide the best possible results, it also does not require large financial investments for the installation of energy storage systems. It is therefore closer to the implementation on actual railway systems and shows an important advantage of the analyzed coordination.

5. Conclusion

In this paper, an algorithm for energy- and cost-efficient control of the electric railway system is presented. The algorithm is based on the hierarchical coordination of the electric traction substation energy flows control level (higher) and individual trains traction energy consumption control level (lower) and is verified by means of a detailed case study. The results presented show promising savings possibilities, which reach up to 45% cost reduction and 40% reduction of energy consumed compared to the non-coordinated case in which trains are optimally driven.

Each level of the presented modular control system contributes to the increase of savings, while keeping the possible implementations of the control system flexible and adaptable to various railway system configurations. Through interactions with the power grid, the system is transformed from a passive energy consumer to a proactive user able of responding to various grid demands as well as providing services to the power grid operator.

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