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Towards Smart Railways: A Charging Strategy for Railway Energy Storage Systems

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Abstract

The huge power requirements of future railways require the usage of energy-efficient strategies towards a more intelligent railway system. The usage of on-board energy storage systems enables better usage of the traction energy with a higher degree of freedom. In this article is proposed a top-level charging controller for the on-board and wayside railway energy storage systems. Its structure comprehends two processing levels: a real-time fuzzy logic controller for each energy storage system, and a genetic algorithm meta-heuristic, that remotely and automatically tune the fuzzy rules weight. As global results, the reduction of regenerated energy is 22.3% with the fuzzy logic controller. With the optimization strategy, this reduction can be further extended to 28.7%. The need for a smart railway framework is also discussed towards a realistic implementation of such charging strategy. Thus, with a high degree of flexibility, the efficiency of railway energy systems can be increased with the proposed framework.

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1. Introduction

The development of next-generation electrical smart grids is on a rise in past years, with the integration of information technologies into the electrical system. This leads to improved controllability, distributed generation and controlled demand of such power grids. These concepts are now being transported to the railway sector, which comprises a special case of the electrical power system, [1]. Specifically, the objective of the power system is to provide power, whereas the objective of the railway system is to transport passengers and goods.

The railway electrification system is a particular case of a power system, where most of the loads are trains varying in space and time. Also, the interconnection with power grid is made through Traction Power Substations (TPS), usually heterogeneous power grids (strong/weak grids), and the amount of power being handled by each train can vary drastically in a few seconds (for example, a train arriving at a passenger station, depends mostly on regenerative braking – if it is possible – to immobilize the train; after a few seconds, the train accelerates with full torque and power to depart from the station), [1].

Railway transportation is considered one of the most energy-efficient modes of transportation. According to [2], the railway sector had a market share increase of 8.9% between 2005 and 2015 in the transportation of passengers and goods in the European Union. From the latest reports, the rail networks carry 8% of the world's motorized passenger movements and 7% of freight transport, [3]. Besides, this market share is only achieved with a final global energy consumption of 2%, in comparison with other means of transportation.

Since trains are considered one of the most energy-efficient modes of transportation and with the growth from past years, it is necessary to bring the concepts associated with electrical smart grids to this sector. This paper extends the work in [4], where a charging strategy for on-board Energy Storage Systems (ESS) is presented,

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charge". Another variable can be train speed. This variable provides information for near-future energy needs: "if the train is stopped, then it most likely requires high demand for power in near future, for the departure; of the speed is high, then it might be needed to be stored a high amount of energy in the ESS".

However, this is strongly dependent on the train position and on the operation conditions of other trains. Therefore, it is essential to have a broad picture of the electrification system, through a power-flow system state analyser. Such analyser requires that each train reports in real-time the data from energy meters to a remote metering database.

The obtained results also depend on the ESS technology. The chosen unitary efficiency has led to the presented results and it should be considered lower improvements in energy efficiency depending on the ESS technology. However, with the consideration of super-capacitors and SiC transistors that can lead to an efficiency of 98%, the expected results must be closer to the obtained ones. Future research directions are possible with the study of the case study for different parameters (different capacities for ESS, different ratings, different efficiency values, etc.).

In the following section is discussed a practical implementation of the proposed methodology in a smart railway framework.

5. Smart Railway Framework

As previously discussed, the presented charging strategy considers a specific train journey. However, for a practical implementation, a smart railway framework must be considered, as illustrated in Fig. 15.

The hardware for onboard ESS is coupled in each train DC bus. The references for the charging profile came from the “Onboard Smart Railways Processing Unit”, which is a computational platform that reports data from each train to a remote processing unit (represented in Fig. 15 by the cloud) and receives setpoints to improve the energy efficiency.

This cloud-based strategy has been explored in [43], where the knowledge of the electrification power flow is required for the necessary setpoints and a fast communication link provides better actuation.

This generation of FLC rules is performed remotely by the GA, and it must be based on the result of on-board train prediction algorithm: each train generates a prediction, then it compares this prediction with a database of predictions and finally, it updates the FLC rule-set. This strategy is better explained in Fig. 16.

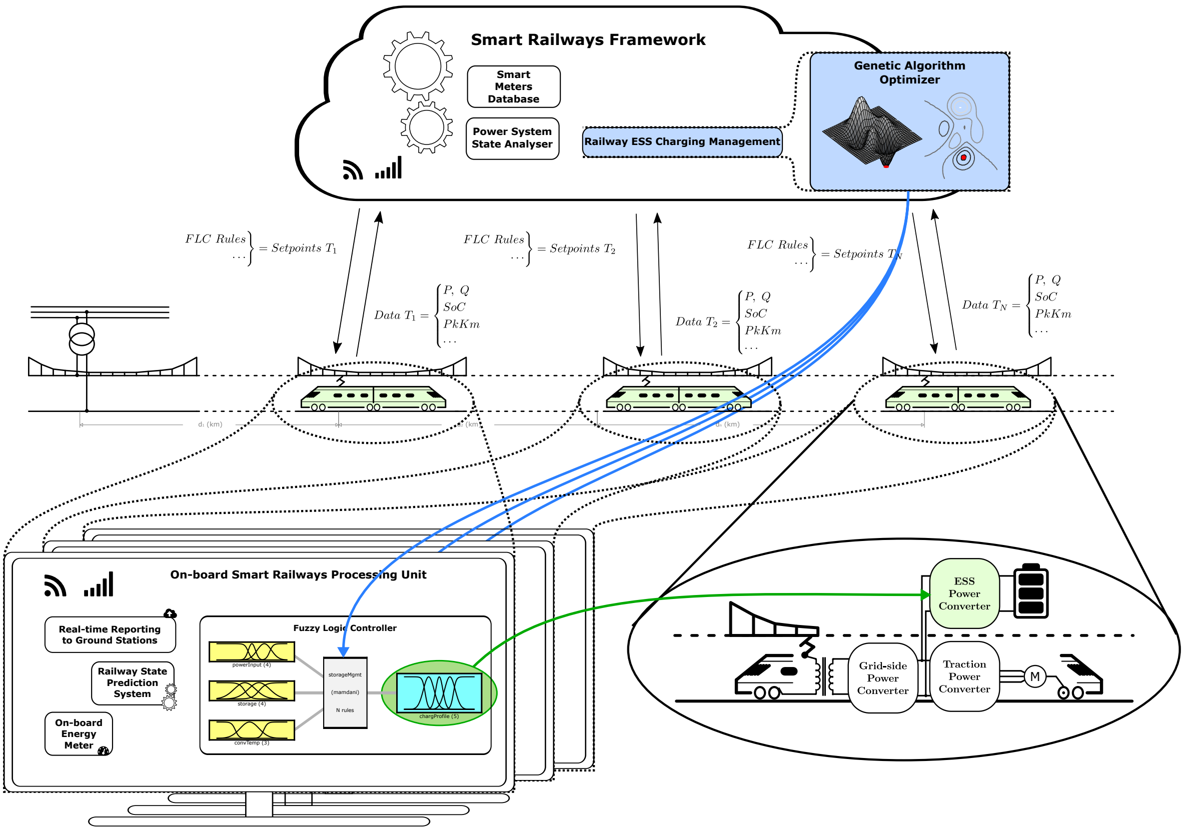

Figure 15. Smart railways framework to support the railway on-board charging strategy for multiple trains.

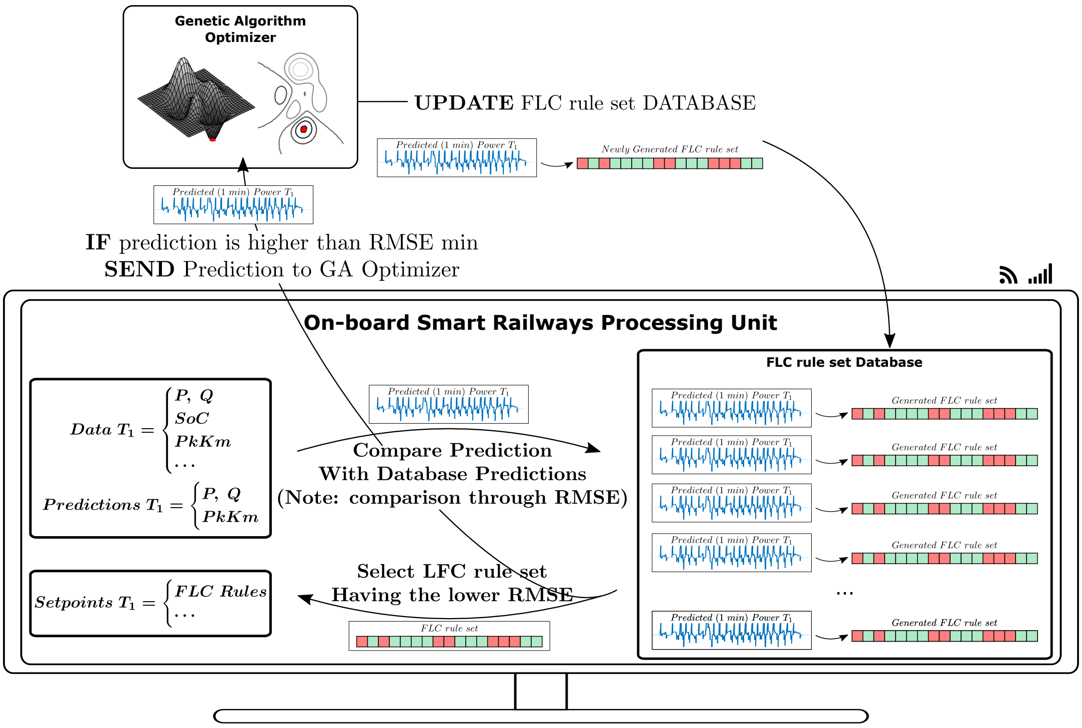

Figure 16. Strategy for real-time operation of on-board smart railways processing unit.

As an example, if the prediction algorithm is capable to generate a one-minute prediction of the train power consumption, then this array of predictions is compared to a database of previously generated FLC rule-sets. The comparison is performed through the Root Means Square Error (RMSE): the prediction is compared with all arrays in the database, in a 1×N approach (where N is the size of the database); then the arrays are ordered and the one having the lower RMSE is selected (specifically, the previously processed FLC rule-set is selected, correspondent to the lower RMSE). It should be noted that this comparison procedure can be fast (as an example, the RMSE comparison of a 1000 points prediction array with a database of 10 000 elements takes around 0.2 s in a modern computer).

Besides, if the predicted power consumption is quite different from any of the elements in the database — the lower value of the comparison RMSE is higher than a minimum RMSE — then the train sends the predicted value to the cloud, and the GA will generate a new fuzzy rule-set for the corresponding array. Finally, this is sent back to all trains (considering that all trains have similar ESS device).

In Fig. 17 is illustrated exactly how the information should flow between the two sides.

This proposed charging strategy can also be included in wayside ESS. In this, it is needed a real-time evaluation of the state of the system. Therefore, it is required that every train has onboard energy meters and these measurements must be transmitted in real-time to a remote database, wherewith such information, is possible to calculate the power flow in the railway electrification.

With this remote power flow analysis and measurements, the wayside can take advantage of the excess of energy injected by each train when they are operating in regenerative braking. Also, the opposite is viable, where the wayside railway ESS can support the departure of trains when their demand is nearly the maximum available torque and power.

In Fig. 18 is illustrated a particular case of wayside ESS, specifically the electric vehicles parked in passengers station parking lot.

In the example of the Fig. 18, the wayside ESS comprises a passenger parking lot, having electric vehicle chargers where the energy for this chargers comes from the catenary. The passenger stations are the points on the line where, naturally, the train mostly needs to brake and accelerate. Therefore, this place is a point of interest to have the power injection. The flexibility of the proposed two-level hierarchical energy management strategy is now demonstrated.

6. Conclusions

The initial approach of a storage charging controller, focused on multiple optimization criteria, and applied to railway transportation systems, is presented here. The proposed strategy is a two-level hierarchical EMS,

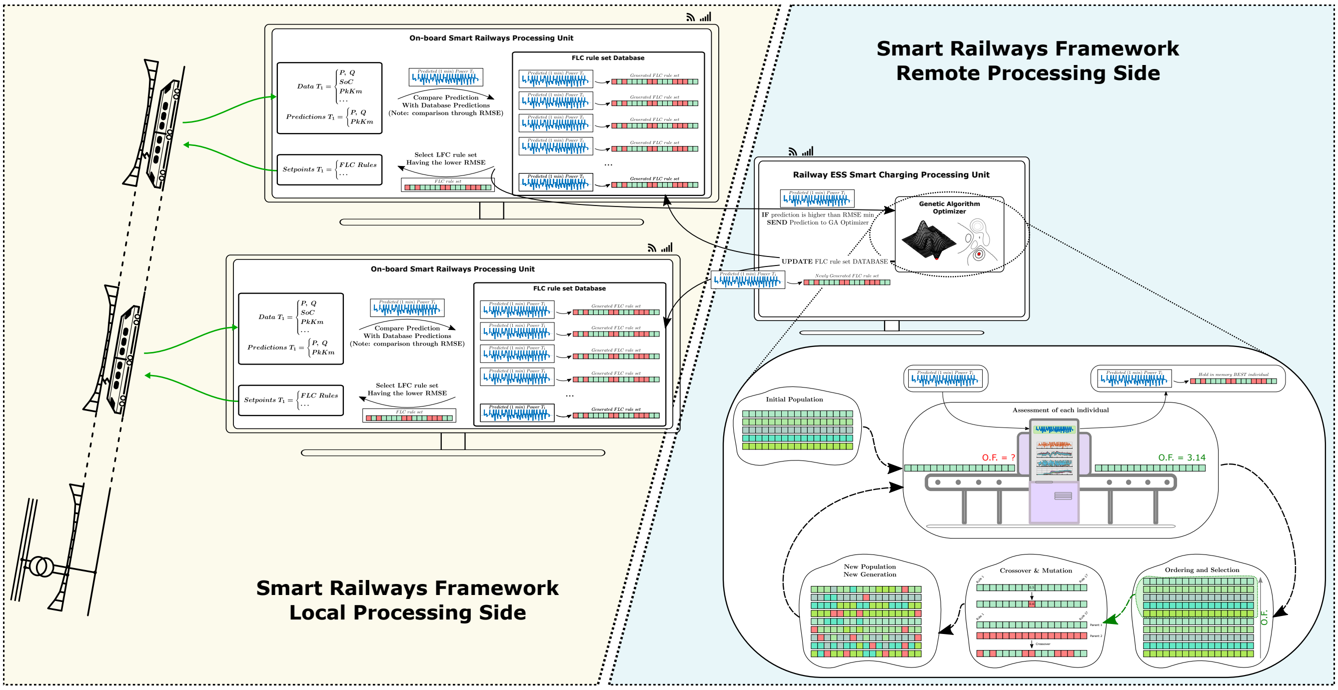

Figure 17. Illustration on the information flow between local and remote processing units.

where the real-time processing level is ensured by a fuzzy logic controller and the higher-level is responsible for the optimization through a genetic algorithm. This optimization strategy combines the knowledge of the expected behaviour of the system, by manually defining the rules of a fuzzy logic controller and, later, a meta-heuristic is used to adjust the weight of the fuzzy rules.

The contribution of this paper was partially demonstrated in the first part of this paper, with a case study of a single train journey. The focus of this work was to validate that a feasible charging solution having multiple input variables can be easily implemented with an FLC. This charging solution can result in the high reduction of the regenerated energy (near 22.3% in the presented case study). Later, as an optimization strategy, a meta-heuristic can achieve 6.4% of regenerated energy reduction, on top of baseline.

With the demonstration of the feasibility of the solution for a single train journey case study, the second part of this paper tries to clarify, with a conceptual discussion, the integration of the proposed algorithms into a smart railway framework for energy management. In here are addressed questions regarding the need to have prediction models in train on-board processing units, and the need to hold a database on the results of the GA outcomes. The big advantage of the proposed algorithm is the ability for automatic learning.

With the discussion on the solution, further research directions have emerged. First, the prediction of the train state is needed to better adapt the real-time operation of the FLC. Then is required a power system state analyser, that is capable to generate the knowledge on the global railway electrification state. This task is computationally demanding since not only it requires the collection of all power consumptions of all trains, as well as their geographical positions, but also, it needs to automatically calculates the power flow in the catenary. Not only this task performs the calculation for the instantaneous time-stamp, but also for the prediction time window.

A reliable communication link is also required for the operation of the proposed strategy. With a well-designed software solution combined with faster computational resources and with a faster communication link, it is enabled the operation of this energy management system with good performance. The lower the latency between the data acquisition and the decision, the better the operation of this strategy.

The valid demonstration of the proposal together with the relevant scientific contributions leads to the conclusion that with a smart railway framework it is possible to increase the railway energy efficiency, with a high degree of flexibility.

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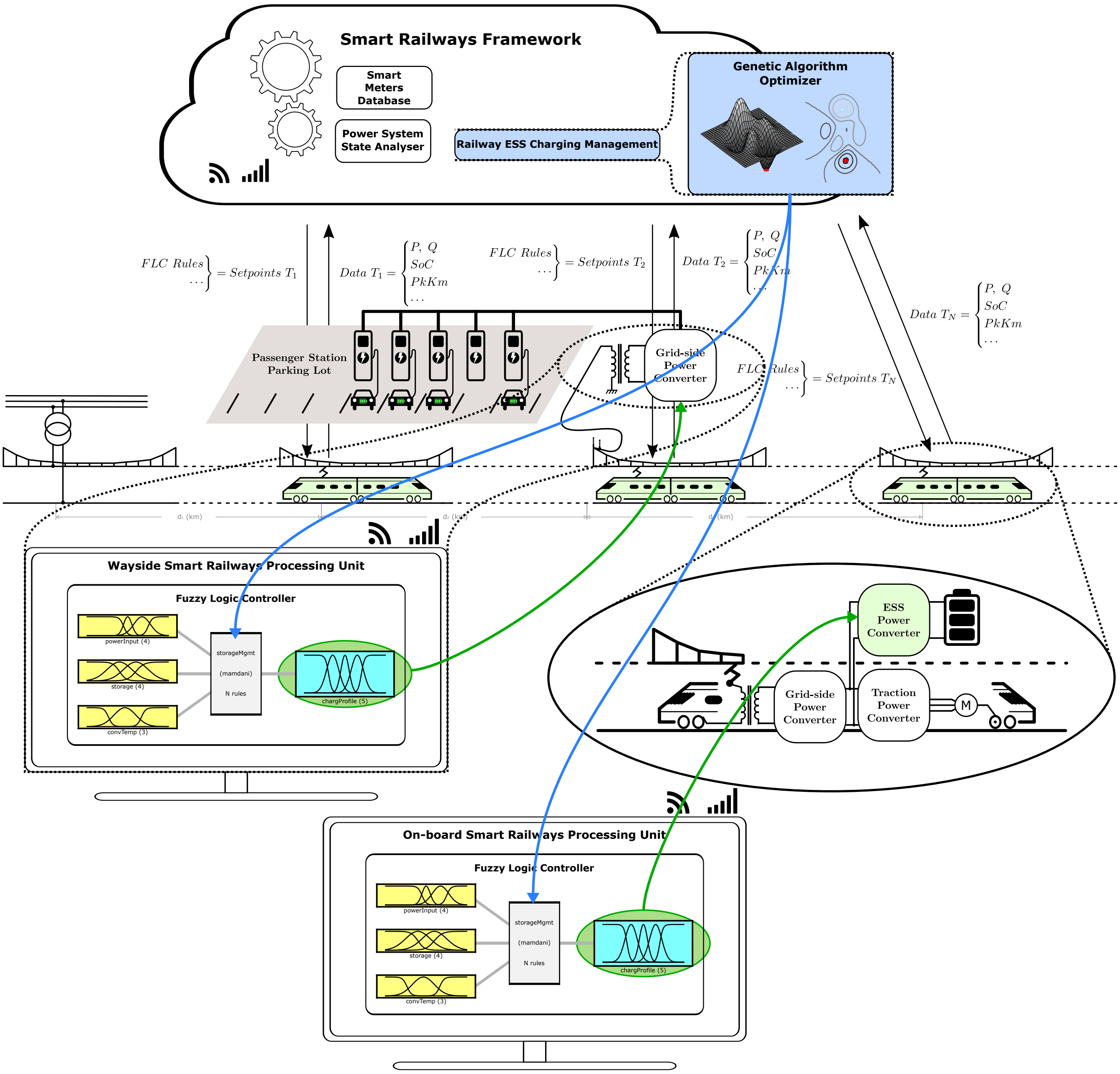

Figure 18. Smart railways framework to support the wayside and on-board railway charging strategy.

Conflicts of Interest

The authors declare no conflict of interest.

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