Optimal Operation of a Smart Electrified Traction System: A Review

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***Abstract*—Smart Electrified Traction Systems (SETS) may play a pivotal role towards the decarbonization of the transport sector and the integration of renewable energy sources. For this reason, the paper proposes an up-to-date state of the art review of the main configurations, operational schemes and flexible assets forming these networks. Also, the intrinsic flexibility of these tractions systems calls for the optimal management of the assets in order to minimize the operational costs. This paper also reviews the main formulations of customized optimal power flow problems, which incorporate the intrinsic features of these networks. The critical analysis focuses on the reformulation techniques or algorithms adopted to overcome non-linear and non-convex constraints, typical of optimal power flow problems.**

***Index Terms*—Smart Electrified Traction Systems, Energy Management, Distributed Energy Resources, Optimal Power Flow, Optimization.**

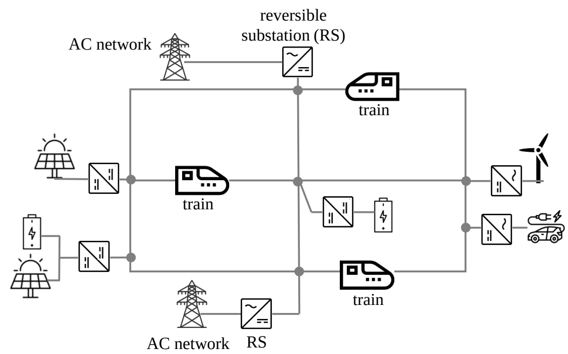

Fig. 1. DC-power SETS scheme.

I. Introduction

In Europe, transport significantly contributes to the total carbon emissions and it represents the main cause of air pollution in cities. It is evident that the ongoing energy transition towards a low-carbon paradigm shall envisage clear action fostering sustainable transports [1]. In this context, Smart Electrified Traction Systems (SETS) may play a pivotal role. Notably, a SETS envisages the integration and management of a variety of flexible assets in a traditional electrified traction network, which are added to the typical transportation loads, e.g., trains or trams [2]. These networks are implemented both in Direct Current (DC) and Alternating Current (AC) power. A possible configuration of a SETS is in Fig. 1; for simplicity, a DC-power SETS is depicted. Besides the transportation network (grey grid) and the typical loads, it is worth noting the presence of Renewable Energy Sources (RES) plants, which inject power directly into the SETS. Flexible assets, such as Energy Storage Systems (ESS) (e.g. batteries) and charging stations for Electrical Vehicles (EVs) can also be connected. These may be in standalone configuration or in co-location with other RES plants. Finally, Reversible Stations (RS) connect the SETS to the main AC power network, allowing for a bi-directional operation. In other words, differently from a standard configuration where the SETS can only absorb power from the AC network, RS allows for power flows from the SETS towards the main AC network. As for other contexts (e.g. micro-girds, energy communities), the intrinsic flexibility of a SETS may be exploited to lower the operational costs by reducing the energy consumption from the main AC-grid, while increasing the reliance on local RES. However, differently from other contexts, the power absorbed by trams or trains varies not only in time but also in location; it also largely depends on the operational phase, i.e. acceleration, cruise and braking. For instance, during the braking phase, a train may implement Regenerative Braking Energy (RBE) [3]. Instead of dissipating this energy via an onboard rheostat, adjacent trains may absorb such power injection; the latter can also be directed to the main AC grid via a RS, stored by means of ESS or employed to feed the electrical loads of a relatively-close passengers' station. These particular features require the development of *ad-hoc* formulations of an Optimal Power Flow (OPF) in order to assess the optimal operation of a DC or AC SETS. The resolution of these problems may rely on re-formulation methods or on nature-inspired algorithms to overcome the non-linear and non-convex features of an OPF. Given the centrality of the topic and the high number of related-works appearing in literature, a review on the main configurations and assets integrated in a SETS, together with an analysis of the main methods to solve AC and DC OPF in the context of a SETS would contribute and facilitate this research path. The characteristics of different SETS are reported in [4], which focuses on current and future network configurations. The review analyses the main structure of railway catenaries. Another review paper [5] addresses the

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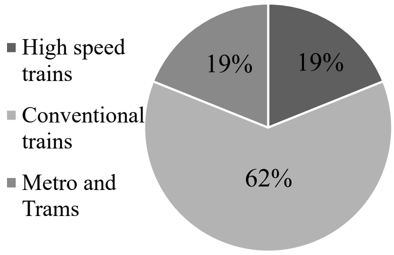

Fig. 2. Statistics on the types of transportation system analysed.

benefits and complexities concerning the integration of ESS and RS within SETSs. In particular, the review categorizes the different available technologies and discusses their market readiness. Both these works focus on characterizing the structure, advantages and issues related to specific SETS components without considering the methodology to optimize their design and operation. These topics are included in [6], which deals with the assets' configuration in a SETS, while extending the discussion to the optimization methods used in literature to compute its optimal operation. The proposed work builds on the approach in [6] and provides with an up to date state-of-the-art review in the context of SETSs. In its first part, this review addresses the main configurations and assets of a SETS; in the second part, it focuses on the main methodologies adopted to solve the OPFs in the context of a SETS.

II. Configuration and assets

The implementation and operation of a SETS depends on its AC [3], [7]–[18] or DC [19]–[41] configuration. For example, the number and type of power electronics converters and conversion sub-stations might depend on the operational scheme adopted. In this context, more than 60% of the references considered in this work deal with a DC SETS, whereas the remaining ones address AC schemes. Besides the operational scheme, Fig. 2 classifies the SETSs with respect to the type of transportation system. The first group of references - [7], [9]–[11], [15], [16], [18] - refers to high-speed railway systems. This accounts for 19% of the total references analysed in this work. The majority of the references (i.e. 62%) addresses conventional railway systems ([3], [8], [12], [13], [17], [19]–[21], [23], [25]–[30], [32], [33], [37]–[39], [41]–[43]). These two types of networks pertain to sub-urban configurations, where trains serve relatively-long distances. Finally, the remaining 19% of the references ([20], [22], [24], [34]–[36], [40]) focus on urban systems, typically adopting trams and metros. These coaches frequently start-and-stop, adopting various speeds based also on traffic conditions. The following subsections highlights the main flexible assets in a SETS (see Fig. 1); studies focused on only one asset are discussed in the relevant subsection, while those evaluating multiple assets are included in the subsection that better captures their modelling features.

A. Reversible Stations

On the one hand, optimized driving strategies, combined with RS and Energy Storage Systems (ESS) can reduce the SETS' energy request from the main AC grid by 15%-30%, as pointed out in [27]. On the other hand, the implementation of RBE strategies may increase the likelihood of overvoltage events, especially during low demand periods. As a consequence, this may potentially damage protection devices as illustrated in [34]. Moreover, optimized driving strategies have been successfully reported to assist the accelerating phase of nearby trains [21], [27]. In other works, the implementation of RS improve energy utilization by 6.9% better granting the integration of RBE [21], although higher network losses are observed, especially when the power flow direction is from the SETS to the main AC grid [23]. A realistic traffic model for railway operation with large perturbations is proposed in [25], which computes potential savings stemming from the use of RS. Finally, the integration of RS and hybrid ESS aims to maximize the power flow towards the AC grid in a high-speed railway system [16].

B. Energy Storage Systems

The integration of an ESS in a SETS enhances the benefits of implementing RS. The RBE energy can be stored and then conveniently employed, at a later time, to sustain the consumption of the SETS or directed to the main AC-grid. Note that ESS units can be locates wayside in dedicated containers or onboard, thus moving with the train. The methodology illustrated in [14] and [9] envisages a wayside ESS that contributes to the optimal operation of the SETS. The study [14] analyses the financial viability of the necessary investment. In [9], energy and operational cost savings of 9.63% and 33.22% respectively are reported after the integration of an hybrid ESS along with RES plants in the SETS. The studies in [22] and [26] propose a methodology that computes the optimal location and sizing of an ESS. Results indicate that storages characterized by high power ratings and small energy capacities are more effective. An extension of these studies is in [24] with the inclusion of time-dependent budget constraints. A detailed performance assessment between wayside and onboard ESS is carried out in [19]; the former implementation is able store and manage higher amounts of RBE (44.9% of the total) compared to the latter system (29.1%). The gap reduces with heavy traffic conditions [37]. The optimal operation of a SETS grants 21% reduction in the daily energy costs if the ESS operates alongside PV systems [28]. The implementation of advanced setups with hybrid ESS solutions and PV plants lower the SETS' operational costs by 47% [17]. Other frameworks envisage the swapping of an onboard ESS in strategically located exchange points, granting a continuous service operation but with higher maintenance and operational costs [36].

C. Photovoltaic plants

The integration of PV plants on standalone configurations or in co-location with ESS enhances the techno-economic management of a SETS. A realistic example in [30] refers to a SETS in Italy, which envisages the presence of a PV plant. The latter helps to maximize the net present value of the integrated infrastructure. On the one hand, almost 98% of the annual PV energy contributes to the operation of the railway network, while reducing the overall network losses. On the other hand, the high investment costs due to the PV plant and the necessary DC-DC power electronics converter leads to a payback time of 18 years. A similar setup, where wayside PV systems operate with PV panels at the passengers' station, is applied in [15] to the case of a high-speed railway network. The return on investment proved to be positive over a 25-year

TABLE I

SUMMARY OF THE ASSETS IMPLEMENTED IN THE ANALYSED LITERATURE

Reference	Reversible Substation	ESS Location	Photovoltaic	Wind Turbines	Electric Veichles
[22], [24], [26]	-	substation	-	-	-
[23]	✓	-	-	-	-
[19]	✓	onboard & wayside	-	-	-
[25]	✓	-	-	-	-
[27]	✓	substation	-	-	-
[14]	✓	wayside	-	-	-
[37]	✓	onboard	-	-	-
[30]	-	-	✓	-	-
[28]	-	wayside	✓	-	-
[15]	✓	-	✓	-	-
[16], [38], [40], [42]	✓	wayside	✓	-	-
[17]	✓	substation	✓	-	-
[3], [36]	✓	onboard	✓	✓	-
[7], [10], [12], [43]	✓	wayside	✓	✓	-
[9]	✓	substation	✓	✓	-
[41]	✓	wayside	✓	✓	✓
[39]	✓	wayside	✓	-	✓
[31]	✓	wayside	-	-	✓

investment horizon. A Monte Carlo simulation approach is developed in [38] to manage the intrinsic uncertainty of the PV output, while predetermined scenario-based simulations are presented in [12]. Besides the presence of PV plants, the SETS in [38] considers the opportunity to smartly manage the RBE. The PV output and the RBE in a SETS are managed by an ESS, letting a 35% and a 14% reduction in the overall operational costs, in [40] and [42], respectively.

D. Wind plants

An important feature of a SETS is the possibility to integrate the energy granted by wayside wind plants, as in Fig. 1. Moreover, the literature reports on effective solutions envisaging specific wind turbines directly installed on top of the trains and thus moving with them. This solution has the intrinsic advantage that the wind turbines would always face the main direction of the wind flow, avoiding the need for orientation systems. A specific setup is proposed in [44]; here, the wind turbine is activated during the train's braking to facilitate the vehicle stopping, without increasing the vehicle's drag during motion. A combined setup for a SETS is studied in [43], with the presence of wind plants, PV plants, and hybrid ESS (i.e. supercapacitor and batteries) allowing for a 7.9% reduction in the operational costs compared to a traditional system. References [3], [7] and [10] analyse a similar setup confirming similar costs' reductions.

E. Electrical Vehicle (EV) charging infrastructure

The work in [31] proposes a framework to exploit the RBE to power the electricity consumption of metro stations. The implementation of a dedicated DC microgrid lets the charging of electric buses connected nearby the stations. Furthermore, as detailed in [39], integrating a Vehicle-to-Grid setup reduces the overall operational costs of the transportation network. In fact, the EVs - through the dedicated charging station connected to the SETS - may temporarily contribute to the power demand of the railway network. The energy management strategy in [39] makes a more effective use of the available RBE and the PV energy when EVs are also connected to the SETS and thus able to absorb such energy. Finally, [41] highlights the integration of a fast-charging EV station within a DC medium-voltage SETS, which also include PV and wind plants together with ESS. Such a combined setup lowers the energy-dependency from the main AC grid.

III. OPTIMAL POWER FLOW RESOLUTION METHODS

Most of the abovementioned works have investigated the optimal management of a SETS. The operation of the integrated assets (e.g. ESS, EVs, PV plants, etc.) can be managed together with the scheduling of trains/trams in order to reduce, for instance, the overall operational costs. Minimizing the operational costs whilst respecting technical performance, requires the solution of an OPF. Here, the objective is to determine, at each time step $t = \{1, ..., T\}$, the total active power P_i and (if applicable) reactive power Q_i and the modulus V_i and phase θ_i of the nodal voltages at each node $i = \{1, ..., n\}$. The combination of $\{P_i, Q_i, V_i, \theta_i\}$ has to minimize the operational cost function (1). The formulation of an OPF changes depending on the type of network considered; the general formulations of an AC-OPF, (1)-(8), is proposed below retracing the steps illustrated in [45]. The DC-OPF formulation can be derived from the previous one as detailed in [46]. This formulation lacks the presence of reactive power and only purely resistive impedances are considered.

$$\min_{P_i, V_i, Q_i, \theta_i} \sum_{i=1}^{n} f(P_i, V_i, Q_i, \theta_i) \tag{1}$$

$$s.t.\ P_i = \sum_{j \in i} y_{ij} V_i V_j cos(\theta_i - \theta_j + \phi_{ij}) \quad i = \{1, ..., n\} \tag{2}$$

$$Q_i = \sum_{j \in i} y_{ij} V_i V_j sin(\theta_i - \theta_j + \phi_{ij}) \quad i = \{1, ..., n\} \tag{3}$$

$$P_{min} \leq P_i \leq P_{max} \qquad i = \{1, ..., n\} \tag{4}$$

$$Q_{min} \leq Q_i \leq Q_{max} \qquad i = \{1, ..., n\} \tag{5}$$

$$V_{min} \leq V_i \leq V_{max} \qquad i = \{1, ..., n\} \tag{6}$$

$$\theta_{min} \leq \theta_i \leq \theta_{max} \qquad i = \{1, ..., n\} \tag{7}$$

$$\theta_1 = 0 \tag{8}$$

Without lack of generality the time-dependency is suspended; this allows to drop the subscript *t*. Notably the equality constraints (2) and (3) are non-convex. This makes the resolution of an OPF with standard optimization techniques rather complex. A list of possible reformulation techniques is listed in Table II. These are detailed in the reminder of this section.

A. Mixed Integer Linear Programming optimization problems

The works in [12] and [16] investigate the reformulation of the AC-OPF as a Mixed Integer Linear Programming (MILP) problem. To do so, the authors neglect to modelling and assessment of the nodal voltages, focusing only on the power dispatch of the considered assets (i.e. RES plants, ESS, power consumption of trains, etc.). A similar assumption is adopted in [32] concerning a DC-OPF problem, which does not evaluate the amplitude of the nodal voltages in the considered DC-OPF problem. Another simplifying approach, which is valid for AC-OPF problems, envisages the implementation of the so-called “DC power flow” assumptions. In other words, the AC-OPF in [3] considers the modulus of all the nodal voltages V_i equal to 1 and thus no longer decision variables. In addition $\phi_{ij} = -\pi/2$; finally the spread between the voltage phases $\theta_i - \theta_j$ is assumed to be significantly small so that $sin(\theta_i - \theta_j) \approx (\theta_i - \theta_j)$ and $cos(\theta_i - \theta_j) \approx 1$. The modelling of nodal voltages is neglected in [39], letting the OPF resemble a MILP optimization problem. Furthermore, authors in [38] and [17] minimize the daily operational costs of a SETS equipped with PV plants and ESS. A MILP formulation facilitates the resolution of the underlying AC-OPF, although simplifying modelling assumptions on the actual power flows apply. The same approach is implemented in [40], where a DC-OPF for a SETS is reformulated as a MILP optimization problem. Finally, the authors in [42] claim to solve an AC-OPF for the minimization of the operational cost of a SETS considering uncertainties linked to PV production and RBE. However, the management of the nodal voltages of the SETS and thus the implementation of actual AC power flow constraints is overlooked.

TABLE II
OPTIMAL POWER FLOW REFORMULATION TECHNIQUES

Mixed integer Linear Programming problems	[17] [32] [12] [3] [16] [38] [39] [40] [42]
Convex optimization problems	[28] [46]
Non Linear Programming problems	[30] [9] [10] [7] [24] [29] [22] [26] [27] [43] [20]

B. Convex optimization problems

Other methodologies presented in literature opt for a convex reformulation in order to solve the OPF problem for a SETS. For instance, an effective method is Sequential Quadratic Programming (SQP) [47]; the underlying methodology envisages the iterative resolution of quadratic programming subproblems that serve as approximations of the original one. One of the key advantages of SPQ is its ability to improve the convergence to a local minimum from arbitrary initial solutions. This method is applied in [28] where a SETS with PV plants and ESS is investigated. A two-level management framework is implemented. In the first level, an SQP problem optimizes the day-ahead scheduling of the ESS to minimize its operational cost; in the second level, a real-time ESS adjustment, based on fuzzy logic, is enabled to handle the uncertainty of the PV production and the power consumption of the railway substation. Finally, in order to address the non-convex formulation of a DC-OPF problem tailored to a SETS, the methodology in [46] propose a Second Order Cone Programming formulation with auxiliary variables replacing the product of nodal voltages at different busbars.

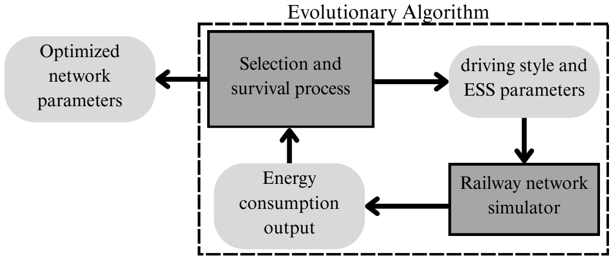

Fig. 3. Representation of the optimization process in [27].

C. Non Linear Programming optimization problems

Often, non-linear and/or non-convex problems are solved by means of a class of algorithms whose methodology mimics the evolution of natural phenomena. Although these methodologies are very effective, they cannot guarantee that the solution found is a global optimum. For example, reference [22] applies Coral Reefs Optimization to determine the ESS location and size in a DC railway network. Simulations take railway traffic scenarios, ESS configurations (location and size), and network topology as input. Hence, the simulations solve the load flow equations using the Newton–Raphson method to check the feasibility of that input set. If so, the corresponding system operational costs for that input set can be computed. The net present value is then evaluated and serves as the fitness function in the Coral Reefs Optimization to update the ESS configurations, iteratively. The work in [26] compares Genetic Algorithms (GA), Fireworks Algorithm, and Particle Swarm Optimization to compute the optimal placement and size of ESS in a SETS. A similar scope is pursued in [24], where a two-stage budget constraint is introduced using GA and Fireworks algorithms. Authors in [9] solve an AC-OPF problem for a SETS with RES plants and ESS using the non-linear solver CONOPT, which is based on the generalized reduced gradient method. In [27], a GA-based model optimizes the driving style of trains and the ESS size to minimize the SETS energy consumption. The method initializes a population of individuals consisting of driving profiles and ESS parameters; these evolve through a *selection-and-survival* processes driven by a cost function. A specific railway network simulator evaluates the fitness of the considered population and thus assesses the overall energy consumption. The latter is sent in feedback to update the initial step until convergence. The iterative process is described in Fig. 3. Authors in [29] optimize a DC railway network using Grey Wolf optimization to minimize the operational cost and the energy loss. In [43], a smart railroad system is optimized using a Micro Genetic Algorithm to minimize the operational costs. Reference [10] optimizes location and capacity of PV plants, wind plants and ESS in an AC railway system to minimize the daily operational costs. Here, the solution of the AC-OPF is found with Brute Force search, exploring all possible solutions to identify the upper and lower bounds of the objective function. It is worth noting that the proposed AC-OPF neglects the assessment of the reactive powers. A supercapacitor is sized and optimally managed in a DC urban rail system in [20] through a bi-level strategy. The first level finds the optimal rated capacity of the ESS considering its capital costs, whereas the second level optimizes the ESS operation. This is performed through by a Particle Swarm Optimization algorithm. Authors in [30] optimize the size of a wayside PV plant in a DC railway network by discretizing the domain of possible PV capacities, and solving the load flow equations for each configuration. This Exhaustive Search method allows to understand the system behaviour under known conditions and find the PV capacity that maximizes the net present value of the investment. The AC-OPF problem in [7] deals with a SETS envisaging wind plants, PV plants, ESS and the management of the RBE and the energy exchange with the main AC-grid. The employed methodology relies on the Differential Evolution Algorithm.

IV. Conclusion

Driven by an increasing interest within the research community, this review explores the configurations and the flexible assets integrated in a SETS in order to enhance its operation and minimize the associated costs. Results indicate that the technologies showing a higher impact in terms of cost savings result to be a combination of distributed RES and ESS, supported by RS allowing bidirectional power flow towards the grid. Moreover, the paper has analysed the techniques adopted to solve the OPF, which determines the optimal operation of the SETS accounting, inter alia, for network-performance constraints. Results indicate that the intrinsic non-linear and non-convex constraints of an OPF are often neglected or reformulated in order to resort to a MILP or, in general, convex problems. The authors wish to emphasize that a research path aiming at the implementation of more sophisticated reformulation techniques should be pursued. In fact, many papers, implementing simplified methods, overlook important operational aspects (e.g. the nodal voltage management or the power flows in the lines). Alternatively, nature-inspired heuristic algorithms stand as a common option, although they cannot guarantee that the obtained solution reaches the global optimum.

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