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Railway Electrical Smart Grids

An introduction to next-generation railway power systems and their operation.

In the last decade, the development of next-generation electrical smart grids (ESGs) has been one of the priorities in the field of electrical engineering, both for most of the research centers and for the industry. In short, an ESG consists of the integration of information technologies into the electrical system to improve its controllability. In traditional power systems, the control has been carried out only by the power plants and some elements of the grid (transformer tap-changers, compensation capacitors, and reactances), whereas, in the next-generation smart grids, most of the elements can respond to control orders from the system operator, which allows, for instance, for the integration of the distributed generation and the demand into the control schemes of the power system. Because of this improved controllability, ESG technologies promise a significant improvement in the capacity utilization, the reliability of the system, and the energy efficiency of the grid.

Although rail power systems (RPSs) are a special case of electrical power system, they are operated in a very different way. While the goal of the power

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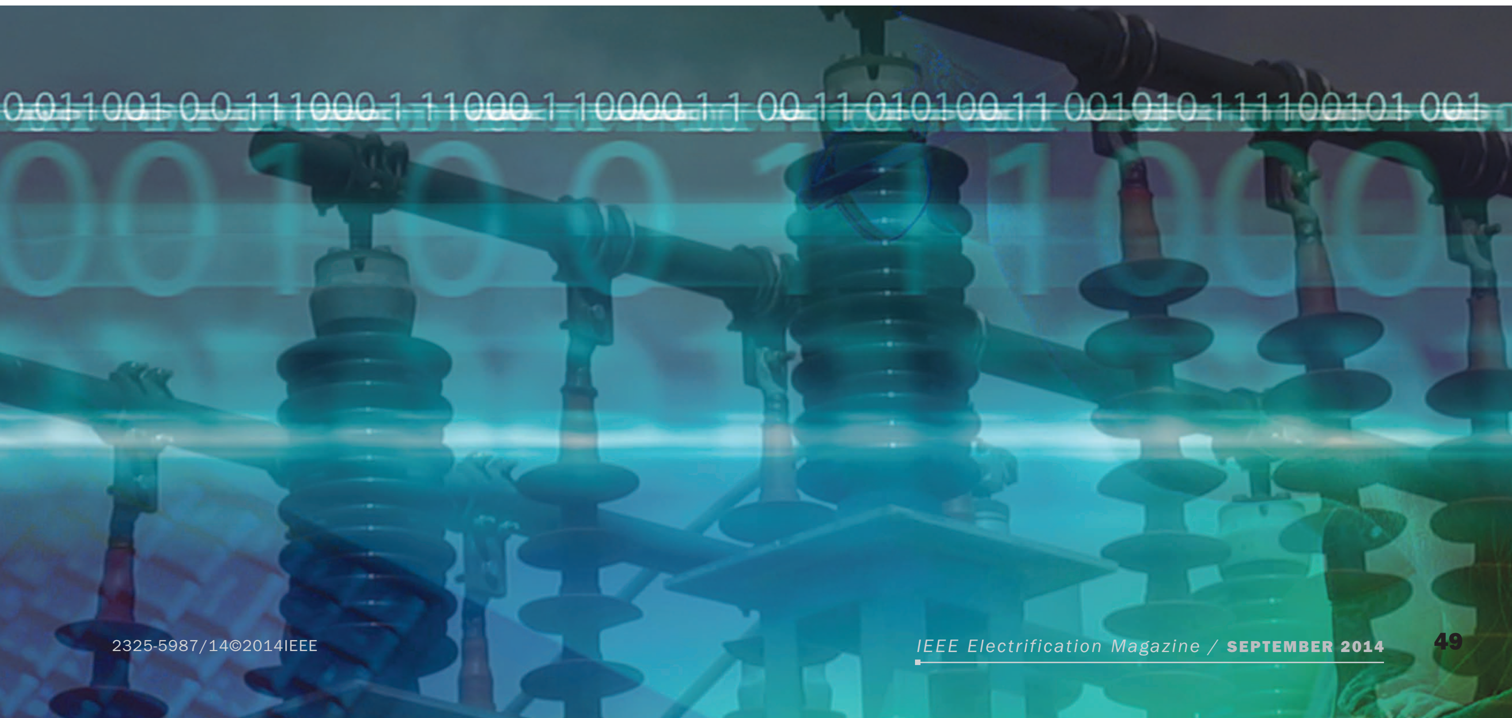

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system is to provide electrical power with the agreed characteristics, the final objective of the railway system is to transport passengers and goods according to a schedule. For that reason, the operation of a railway ESG (RESG) has to be different from conventional ESGs.

Most of the RPSs share some characteristics that make the development of specific ESG technologies adapted to railways particularly important.

1) Most electrical loads are trains, which are spatiotemporally varying loads. The consumption of the trains is related to the way each train is driven, which allows it to even become a generator for a limited amount of time when braking. Just by stopping acceleration and starting braking, the load can vary from 10 to –8 MW in a few seconds. The RPS has to be able to deal with these changes, which occur very often along a given journey.
2) Electrified railways are normally considered one of the most energy-efficient modes of transport, especially over economically viable operating distances. Its potential for energy savings is largely due to regenerative braking, whose efficiency depends largely on when and where it is carried out.
3) Railway lines normally cross wide areas and, therefore, are often interconnected to several electrical grids, which are normally heterogeneous, as strong grids coexist in the field with weaker grids. A smart control that takes into account the specificities of each network is crucial to improve the overall reliability and capacity utilization.
4) An RESG relies heavily on good bidirectional communications between trains and the infrastructure, which is sometimes difficult to achieve, for instance, in tunnels or in remote areas.

This article describes railway power systems and their operation. In addition, the main control actions that can be performed by an RESG are introduced, explaining how they can improve the performance of traditional RPSs, e.g., reducing costs, increasing energy efficiency, and enhancing reliability.

Railway Power System Grids

System Description

As shown in Figure 1, RPSs normally take the electricity from other power systems, which, in turn, have their own generation plants and electrical grids (transmission grid for bulk power transfer, and distribution grid for retail power supply) and whose characteristics may vary significantly (strong grids coexist in the field with much weaker grids).

In liberalized electricity sectors, the transmission, distribution, and generation activities are typically carried out by different companies. The electrical system operators (ESOs) are the companies in charge of balancing generation and demand and operating the transmission grid in such a way that the reliability of the system is guaranteed. The distribution system operators are companies that operate the distribution grids in such a way to ensure that electricity is supplied to every customer with the required quality. Finally, the generation companies are responsible for producing the energy that has been programmed in each power plant. The energy produced can be sold by means of contractual agreements or in organized electricity markets (generally spot markets, including day-ahead and intraday sessions), operated by an electricity market operator. However, final corrections to the program are introduced by the ESO to solve technical restrictions and to respond to the unexpected variations that occur in real time.

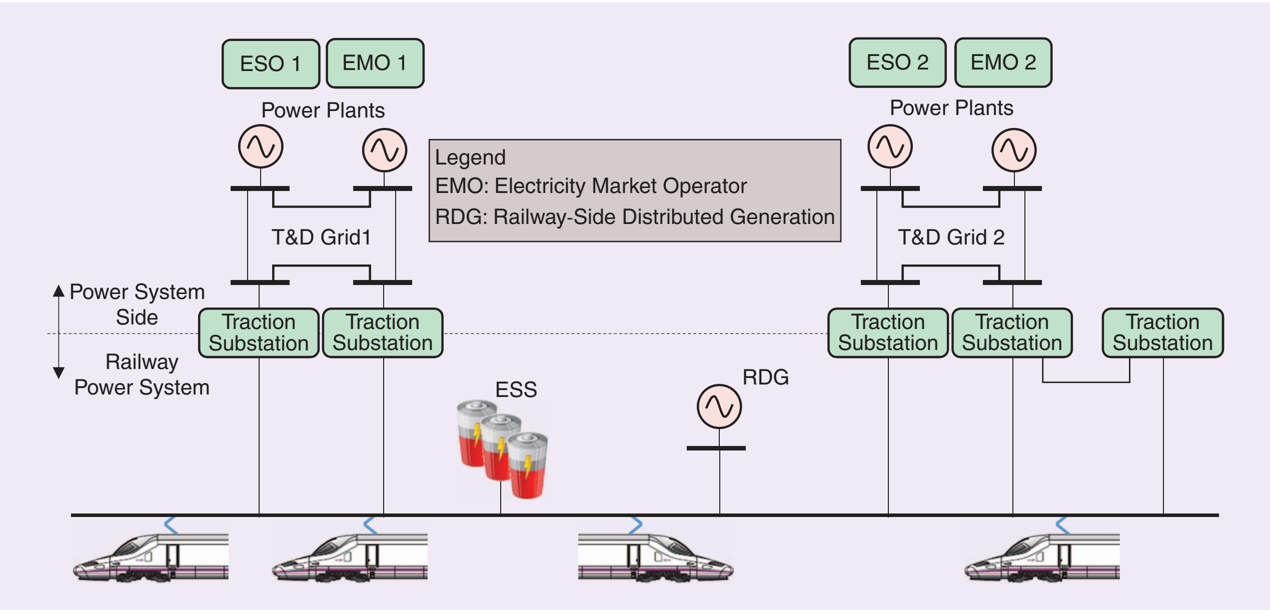

Figure 1. The interconnections of railway power systems to other power systems.

In some countries, some transmission and distribution (T&D) grids and power plants, owned by railway companies, are used specifically for traction purposes. Because of their usage, these grids have particular characteristics (e.g., two-wire, single-phase lines using a low frequency of 16.6 Hz).

Regarding the railways side, when it is not vertically integrated, the infrastructure manager [referred to as the *railway system operator* (*RSO*) as an analogy with ESOs in power systems] plays a dual role: 1) regulating the traffic to ensure safety and an adequate flow of trains and 2) controlling the railway power system. The train operators are independent companies whose activity is to transport loads or passengers with trains. As users of the railway infrastructure, they must pay for the services they use, including power supply, to the RSO.

As shown in Figure 1, RPSs are connected to transmission or distribution grids by means of traction substations (TSSs). It should be noted that not all TSSs are fed directly from the T&D grid: sometimes railway-side electrical lines connect several TSS. In the case of dc-fed railways, substations include transformers and rectifiers. In the case of ac-fed railways, substations include mainly transformers and, when the frequency of the T&D grid and railways is different, frequency converters (static or rotary).

Although they are not widely used, energy storage systems (ESSs) allow the temporal excesses of power to be stored and used later in a deferred way.

Finally, the railway power plants (referred to as *railway-side distributed generation* (*RDG*) in Figure 1) are generators (typically distributed sources of energy) controlled directly by the RSO, which allows for railway-oriented operation, and connected directly to the railway grid.

The Operation of Electrified Railways

Control of the System

The operation of an electrified railway includes two different facets that have to be controlled in a compatible way: 1) the traffic flow operation (which refers to the way the trains move) and 2) the electrification operation (which refers to the way the power is supplied). Therefore, the control centers of the railway are charged with supervising and operating both the traffic and the electrification.

To ensure the safe and efficient operation of the railway, a signaling system is typically in place to manage the traffic flow. The traffic control is typically structured in layers. First, a protection layer is responsible for the safety of the train movements and is in charge of giving the orders to ensure that no train leaves its safe operation conditions (for instance, by getting too close to another train or by exceeding its maximum speed in a specific section). Depending on the specific technology used in the signaling system, the degree of automation of the control may be very different: from manual control (based on visual signals and relying on a person taking the right actions) to fully automated control (based on communications and relying on a control unit to ensure that the system is always in a safe state). Additional layers, always subordinated to the protection layer, are commonly used to improve the quality of the traffic flow according to different criteria (such as punctuality and regularity). The control related to energy consumption optimization would correspond to these operational layers.

The electrification has a similar architecture. A first layer, in charge of protecting the electrical equipment and infrastructure, continuously checks if all of the electrical quantities (voltages, currents, etc.) are within the allowable range and, otherwise, isolates the failure to avoid further damages. Additional layers are responsible for optimizing the operation of the railway grid by reconfiguring its topology, operating the tap changers of the transformers, etc. Unfortunately, these control actions are quite limited and are often too slow for launching them frequently. Thus, the grid is normally designed to supply power in the worst-case scenario with very few control actions, which leads to quite oversized infrastructures.

Although the traffic and electrification are two facets physically coupled in railways (the electrical loads depend on the way each train is driven and the way a train is driven depends on the voltages and, therefore, on the electrical loads), even the upper layers of these two control systems are usually completely uncoupled.

The Operation of Train Services

An important concept for understanding RPS operations is the interrelation between the train movement and its power consumption, which can be used to accelerate the train, to compensate the losses due to running resistance forces—red curves in Figure 2—and/or to feed the onboard equipment (air conditioning, pumps, compressors, lighting, etc.). Similarly, when a train equipped with electrical braking systems brakes, the kinetic energy is converted into electrical power and used to feed onboard equipment, to feed other electrical loads by injecting this power back into the catenary (regenerative brake), or, if none of the previous options is possible, to heat up the onboard resistors installed for that purpose (rheostatic brake).

The power usage related to train movement depends essentially on how the train is driven. The driver, which can be a person or an automatic driving system, decides which force is required to move the train as wanted within the operating limits of the train (see Figure 2)—this depends on the voltage and the speed at which it is operating. Four types of driving actions are normally performed: 1) accelerating, where the traction equipment exerts a force to increase the speed, 2) braking, by exerting a force to reduce the speed, 3) cruising, by exerting only the force required to compensate the running resistance (which maintains the speed), and 4) coasting, when the train does not exert any force at all.

For a given journey duration, a train can be driven in many different ways: accelerating, braking, and coasting differently (in different locations and with different intensities). One driving strategy commonly used for analysis is the

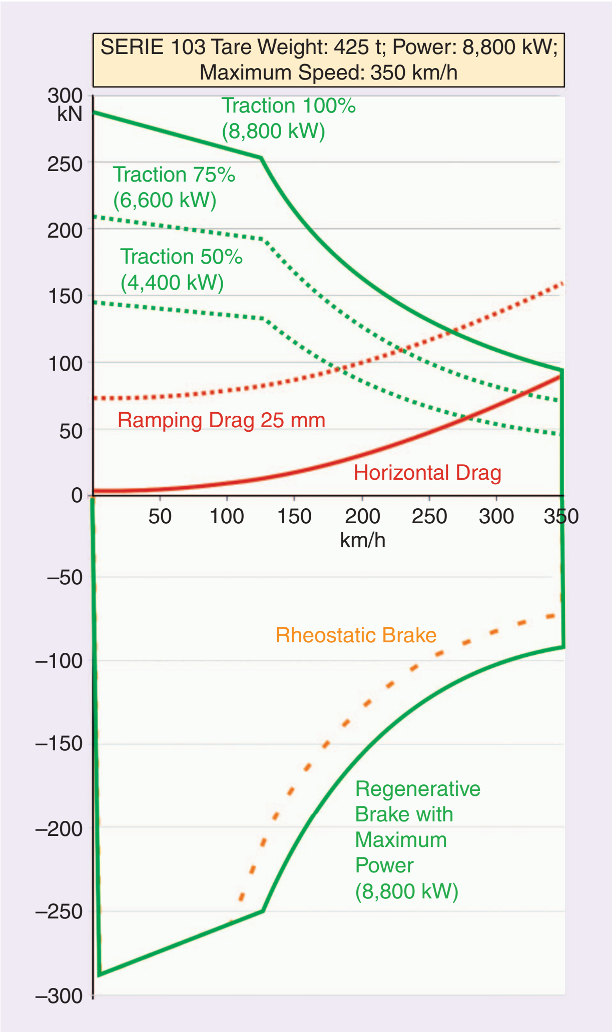

Figure 2. The maximum traction and braking forces for series 103 trains from Renfe, Spain. (Figure courtesy of Luis E. Mesa.)

minimum time driving (MTD), which corresponds to the fastest way of driving while satisfying the limits of the rolling stock and the infrastructure. The commercial driving is normally designed by adding some time margins to the MTD to allow the trains to respond to the small perturbations that occur in real operation (typically delays).

It is important to highlight that each driving style can lead to a very different spatiotemporal distribution of the power consumptions (see Figure 3) and, consequently, to significantly different requirements for the RPS. This flexibility is the key for conceiving smart strategies for driving the trains for many different purposes, such as saving energy and augmenting the traffic capacity.

By managing the traffic and electrification in an integrated way, the RESG can efficiently solve different operation problems that cannot be addressed within the traditional control schemes.

To manage the traffic flow, each train has to fulfill a schedule, which means that it must reach the next station [or the next regulation point (RP)] in the specified time (see Figure 4), within a tolerance (represented in green). The time in these intermediate RPs is checked to allow for a better adjustment of the train driving: if the train arrives too early, it can slow down or, conversely, drive faster if it is delayed.

In the last decade, many researchers have worked intensively to design ecodriving strategies, i.e., driving strategies that minimize the energy consumption of the train. Important energy savings have been achieved by smartly adjusting the coasting sections, which avoids consuming energy that will be given back to the catenary (or wasted in rheostats) later. However, coasting typically augments the trip duration, and, therefore, a tradeoff between energy savings and trip duration has to be found by using optimization techniques.

The design of schedules optimized to enhance operation has also been a very active research topic. For instance, in dc railways, such as commuter trains and metros, the synchronization of departures, arrivals, and driving strategies has been used to improve the receptivity of the contact line (catenary or active rail) when regenerative braking is used, leading to significant energy savings. There are also experiences in which similar techniques have been used to improve the traffic capacity of a line.

Both techniques, ecodriving and the smart scheduling, have been very successful in improving the performance of electrical railways, especially in terms of energy efficiency, when the operation is planned. As they require a huge computational effort, their application to real-time control is very unusual today.

The Next-Generation Railway ESGs

Although improving energy efficiency has often been claimed as the main change vector toward the future railway ESGs, it is important to highlight the enhancement of the controllability of the electrified railways that can be achieved with RESG technologies. By managing the traffic and electrification in an integrated way, the RESG can efficiently solve different operation problems (capacity limitations, changes in the planned operation, etc.), including many issues that cannot be addressed within the traditional control schemes. To allow this, the RESG has to integrate the missions of the railway (to move trains to transport goods and persons) and the electrification (to supply the electricity required by the trains), as represented in Figure 5.

To explain why the RESG can improve the operation of electrified railways, it is important to underline that RPSs are generally not infinite grids. RPSs are normally designed to be able to supply electrical power in the worst-case conditions defined in the requirements, both for normal operation (with all of the elements of the system working properly) and for degraded operation (for instance, assuming the loss of one or two substations). In the design process, a specific operation is assumed, including rolling stock characteristics, train frequencies, and driving strategy (typically MTD). Once the electrification is in service, the operation conditions change as time goes on: the transport demand tends to grow (following the economy growth) and so do the electrical requirements. As long as the operation is less demanding than planned, the electrification can provide the power the trains request. But once the limits of the electrification start being reached (e.g., some line sections are temporally overloaded, the voltage drops become too large in specific points, etc.), the electrification starts creating bottlenecks to the operation at specific peak moments in specific locations. When this occurs, it is, of course, possible to upgrade the electrification by adding some reinforcements (additional conductors to the catenary, new substations, etc.). A different approach would be possible by using RESG technologies: adapting the operation so that the rated limits of the electrification are not exceeded. This is the goal of several ongoing research projects, which are exploring these control mechanisms and developing different RESG technologies. An example is the project MERLIN, a European initiative that is expected to deliver the final results by the end of 2015 (see "The MERLIN Project").

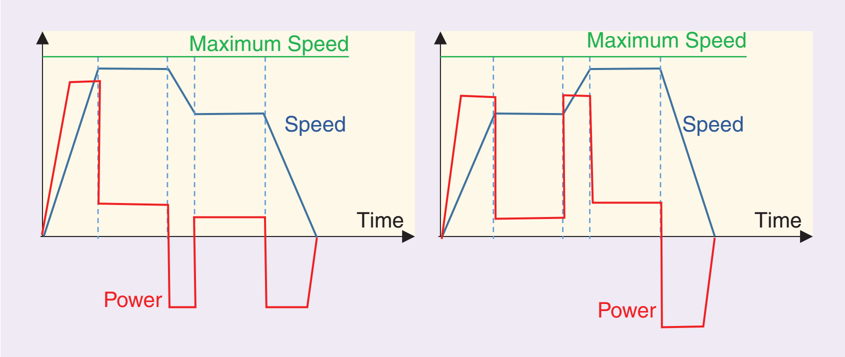

Figure 3. Two examples of different driving strategies for the same trip and duration (single train), leading to different power profiles.

This section describes some of the features that will be possible in future RESGs, grouped into three categories: 1) smart train operation, 2) smart operation of the RPS, and 3) smart interaction with other power systems.

Smart Train Operation

As discussed in the "Railway Power System Grids" section, train driving provides a flexible tool to the RSO to adjust the power consumption profiles to the needs of the system. As the traction energy consumption represents an important part of the operation cost, railway companies have devoted much effort to optimize the driving strategies to minimize the energy consumption. This is normally an offline process where the results are a reduced set of driving strategies, each for a different journey duration.

Smart train driving (STD), i.e., controlling online the way the trains are driven, is the most direct mechanism for performing an active management of the demand (AMD), a key feature in most ESGs, in RPSs. Because of the computational load it involves, optimizing the train driving in a short time is a major challenge the RESG will have to address, especially if a representation of the electrification is included in the optimization model. It should be noted that the main objective of the STD can be very diverse: minimizing the energy consumption, adapting the train consumption to the capacity of the infrastructure in a specific area, and reducing the cost of the electricity.

In Figure 6, in addition to minimizing the energy consumption (case A), which has been taken as the base case, two other types of driving changes are introduced. Case B corresponds to a limitation of the power peak supplied by the electrical grid 2, e.g., due to temporary capacity limitations. Naturally, depending on their type (current or voltage capacity limitations), the power consumption should be modulated differently for better results. If these limitations were at a TSS level (instead of at an electrical grid level), the adjustments would be similar, but covering a different area. Finally, case C corresponds to a transfer of part of the energy consumption from electrical grid 2 to electrical grids 1 and 3, which could be advantageous, for instance, if the prices of the energy were higher in the electrical grid 2 [price-oriented driving (POD)].

It should be noted that, in general, modifying the power profile normally implies modifying the speed profiles and, therefore, the arrival times to the RP. Consequently, in addition to a spatial shifting of the power consumption, a temporal shifting is also performed. When performing POD, this can be useful as electricity prices often vary, not only with the location of the supply but also with the time.

In addition to driving the trains, another important aspect of the smart train operation is the management of all of the

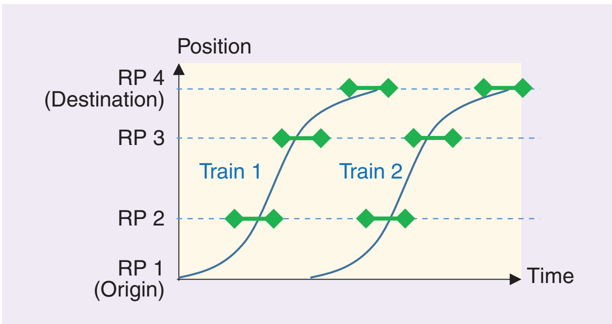

Figure 4. The traffic mesh for two consecutive identical trains.

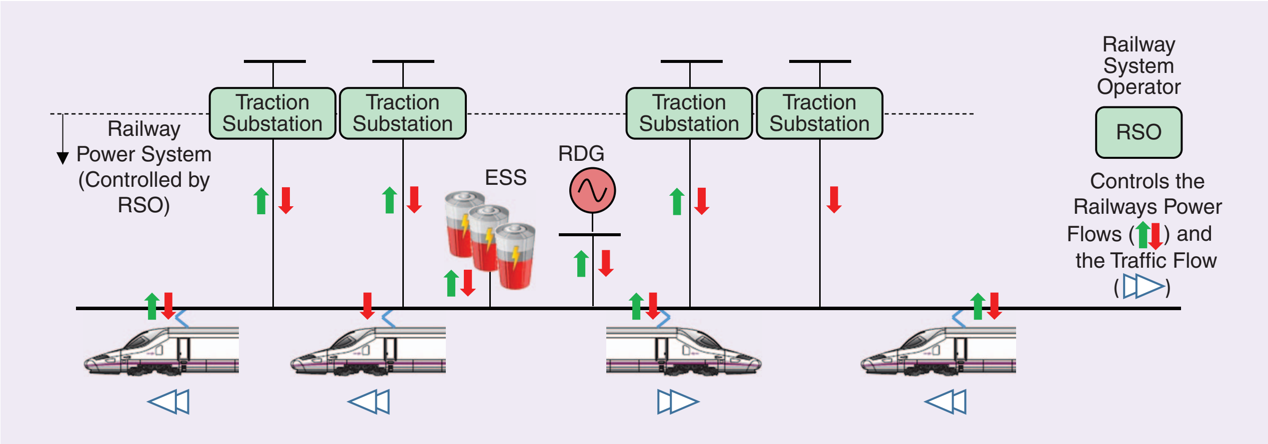

Figure 5. The control of future railway ESGs.

auxiliary loads onboard (e.g., the cooling system of the traction equipment, air conditioning, lighting, and entertainment equipment). Some of these loads can be managed in smart way, modulating the power consumption according to the needs of the system (and the train itself).

Smart Operation of the RPS

RPSs normally have a limited set of controllable devices, including the switching devices (breakers, disconnectors, etc.), on-load tap changers of the transformers, and converters used to connect the RPS to the T&D grid (in 16.6-Hz systems and similar). Because of this limited controllability, the conception of AMD strategies has been, so far, the most common approach in RESG research.

However, this tendency is very likely to change in the future thanks to the advances in power electronics that make it possible to reach higher voltages, transferring more power more efficiently and more affordably. With these technologies, a smart control of the power flows within the RPS would be possible.

Figure 7 compares two different concepts for controlling the power flows. In solution A [Figure 7(a)], the power flow is controlled at every coupling point to the supplying grids (in the TSS) by the controlling devices labeled PFR. Alternatively, in solution B [Figure 7(b)], the controlling devices (PFE in the figure) set the power flows between adjacent sections, which indirectly control the power flow supplied by each TSS. (The ESS and RDG are controlled in the same way as in solution A.)

Regardless of which solution is adopted, controlling the power flows within the RPS can significantly help to achieve the purposes of the RESGs, such as minimizing the

The MERLIN Project

The MERLIN project (http://www.merlin-rail.eu) is an important initiative in the European Union (EU) context that comes up as a response to the fifth call issued by the European Commission as part of Seven Framework Programme. The partnership gathered to achieve the MERLIN objectives is composed of 20 partners from eight EU member states (Czech Republic, Germany, France, Belgium, Italy, Spain, United Kingdom, and Sweden), comprising different European railway systems integrators and equipment suppliers (ALSTOM, AnsaldoSTS, AnsaldoBreda, MerMec, SIEMENS, CAF, and Oltis Group), along with railway operators (RENFE), infrastructure managers (ADIF, RFF, Network Rail, and Trafikverket), supported by consulting companies (D´Appolonia), universities (Newcastle University and RWTH-Aachen University), and research centers and professional associations [the Association of European Railway Industries (UNIFE), the Union Internationale des Chemins de Fer (UIC), and the Spanish Railways Foundation (FFE)].

As mentioned on its official site, the aim of the MERLIN project is to investigate and demonstrate the viability of an integrated management system to achieve a more sustainable and optimized energy usage in European electric mainline railway systems and to provide an integrated and optimized approach to support operational decisions, leading to a cost-effective, intelligent management of energy and resources through:

- improved design of railway distribution networks and electrical systems and their interfaces
- better understanding of the influence of railway operations and procedures on energy demand
- identification of energy usage optimizing technologies
- improved traction energy supply
- understanding of the cross-dependencies between technological solutions
- improving cost-effectiveness of the overall railway system
- contribution to European standardization (TecRec).

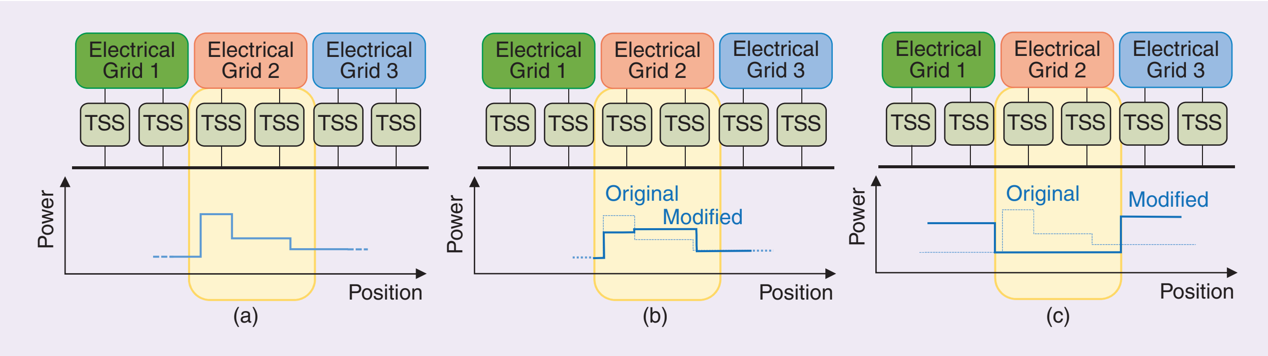

Figure 6. The different driving changes executed to manage the power demand in an RPS: (a) base case, (b) power peak reduction, and (c) energy transfer.

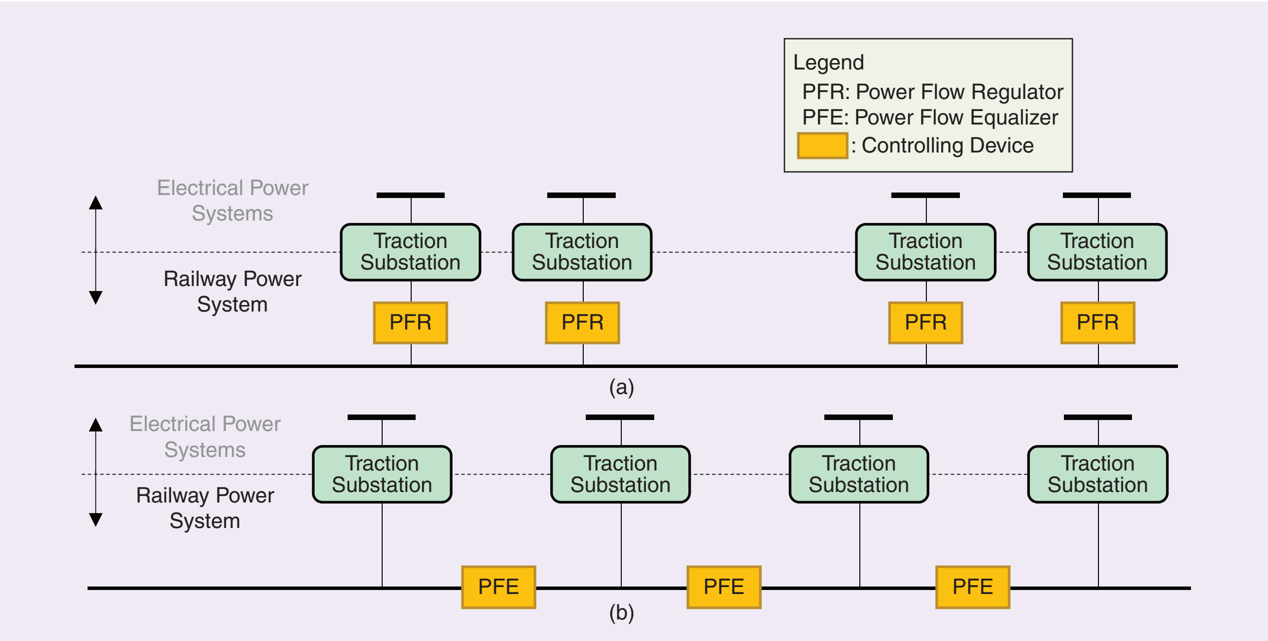

Figure 7. The different strategies to control the power flows in an RPS: (a) case A: control at the power supply points and (b) case B: power equalization.

losses, reducing the cost of the electricity, and smoothening the voltage profiles. But, in addition, as the power flows can be readjusted to come from different TSSs, the reliability of the system is significantly improved. In some cases, this may allow for a reduction of the overrating of the infrastructure elements. (Transformers, converters, and lines are designed to work in conditions that could be avoided or mitigated by using RESG.)

Smart Interaction with Other Power Systems

Probably the most important aspect of the RESGs is the improvement of controllability that can be achieved, which makes it possible to adapt the operation in real time to the oncoming events originated inside or outside the domain of the RPS. Because of their relative size, RPSs have an impact on the T&D grids to which they are connected, which has to be carefully analyzed to avoid nuisances to other customers. But, for the same reason, they can also efficiently help the ESOs and the T&D grid operator perform an appropriate operation.

Here are just two examples of the richer interaction between heterogeneous smart grids (RESGs and ESGs) that will be possible with the adoption of RESG technologies:

- When an incident occurs in the T&D grid and its capacity has been reduced temporarily, the T&D grid operators can prioritize other customers and ask the railway to reduce its consumption from a specific set of substations: the RESG allows it.
- With RESG technologies, in the future, railways could also provide ancillary services (e.g., secondary band regulation) to help balance the generation and the demand in an electrical system.

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