9 Sustainable Electrified Transportation Systems

Integration of EV and E-bus Charging Infrastructures to Electric Railway Systems

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ABBREVIATIONS

DER	Distributed energy resource
E-bus	Electric bus
ERS	Electric railway system
ESS	Energy storage system
EV	Electric vehicle
EVCI	Electric vehicle charging infrastructure
EVCS	Electric vehicle charging station
G2V	Grid-to-vehicle
HFT	High-frequency transformer
HSR	High-speed railway
LRT	Light rail transit
LVDC	Low-voltage direct current
MPPT	Maximum power point tracking
MVAC	Medium-voltage alternative current
MVDC	Medium-voltage direct current
OCS	Overhead catenary system
OPCS	Opportunity charging system
PE	Power electronics
PQ	Power quality
PMSG	Permanent magnet synchronous generator
PSFB	Phase shift full bridge
RBE	Regenerative braking energy
RES	Renewable energy source
RPC	Railway power conditioner
SST	Solid state transformer
T2V	Train-to-vehicle

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TE	Traction energy
TPSS	Traction power substation
V2T	Vehicle-to-train
V2G	Vehicle-to-grid
ZVS	Zero voltage switching

CONTENTS

9.1 INTRODUCTION

During the last several years, investment in developing electric vehicles (EVs) and E-bus charging infrastructures have expanded as the main step by countries to decrease carbon emissions and the use of fossil fuels. In addition, the majority of power supply EV charging stations (EVCSs) can overload the main grid and lead to some indirect emissions. However, the significant amount of energy that is generated by applying regenerative braking in electric railway systems (ERSs) can be adopted as an auxiliary supply. Considering that EVs are parked most hours of the day either at home or offices, their internal batteries can be exploited as promising energy storage systems (ESSs) to save regenerative braking energy (RBE) of trains or even operate as complementary supply ERSs. Integration of ERSs and EV/E-bus charging stations at strategic points, like parking areas close to ERS stations or rail freight intermodal terminals with picked up using of trains RBE as an ancillary supply, can ameliorate the system efficiency and decrease the cost. Meanwhile, the current situation of charging infrastructures can be further improved based on smart grid technology, considering the interaction between these two means of transportation. However, according to the diversity of ERSs, different integration architectures can be defined utilizing the DC or AC energy hub concept. Although several research projects have been conducted on the integration of different transportation charging infrastructures, there is still a long way to achieve the goals regarding the smart grid concept and energy hubs. This chapter, as one of the pioneering studies in this field, proposes different DC and AC hub-based integration architectures and analyzes the incorporation of EV/E-bus charging infrastructures with ERSs. Meanwhile, the concept of train-to-vehicle (T2V) and vehicle-to-train (V2T) technologies, together with the challenges of the architecture of future supplying systems in sustainable transportation, will be explained.

9.2 BACKGROUND OF ELECTRIC RAILWAY SYSTEMS

Electric railway systems (ERSs) have experienced substantial development and evolution in the last several decades due to the increased demand for transportation and the dramatic growth of technology. The historical overview and comprehensive classification of ERS configurations have been addressed in [1]. However, the current ERSs, depending on the main supplying system, can be divided into two main groups of DC and AC systems.

9.2.1 DC RAILWAY SYSTEMS

The DC ERSs were introduced as the first systems with lower requirements and power ratings in transportation networks. Urban ERSs containing subways, trams, and light rails are the most popular types. Depending on the supplying voltage level they can be classified into four groups, as shown in Table 9.1.

The allowable voltage limits are determined according to BS EN 50163 and IEC 60850 standards. These values are determined according to the number of wagons and the distance of the locomotive from the feeding substation. Choosing the right

TABLE 9.1
Different Voltage Levels of DC ERSs

Maximum instantaneous voltage	Maximum permanent voltage	Nominal voltage	Minimum permanent voltage	Minimum instantaneous voltage	ERS voltage
800 V	720 V	600 V	400 V	400 V	600 V DC
1 kV	900 V	750 V	500 V	500 V	750 V DC
1950 V	1800 V	1500 V	1000 V	1000 V	1500 V DC
3 kV	3 kV	3 kV	2 kV	2 kV	3 kV DC

voltage level in a project depends on several structural and utilization conditions. Meanwhile depending on the operation type and power range DC ERSs can be classified into four groups, as shown in Figure 9.1. Urban low-voltage low-power systems known as trams, streetcars, or light rail transit (LRT) are the first category with tracks and trains running along the streets and operating with another road traffic. These systems mostly are supplied by overhead wires with a nominal voltage of 450–750 V DC in the power range of 0.5–1 MW. The second category is dedicated to the urban low-voltage medium-power systems known as subways, metros, or rapid transit systems with the often-underground railway track. These trains mostly are supplied by both third rail systems or overhead wires with a nominal voltage of 750–1500 V DC in the power range of 2–4 MW. Frequently braking and stopping diffused existing DC lines in the city area and similar supply voltage ranges are encouraging features of urban ERSs for T2V integration. Suburban or regional ERSs are the third category that connects suburbs or commuter towns to the center of a city. They mostly are supplied by overhead wires with a nominal voltage of 1500–3000 V DC up to 10 MW. The next category is related to the high-speed railway (HSR) systems with medium-voltage DC (MVDC), which operate at intercity distances and connect inland cities and sometimes international routes. HSR MVDC trains are faster than other groups of trains, adopting special rolling stock and dedicated tracks. The operating speed of HSR MVDC trains usually is more than 250 km/h. The supply system is based on overhead catenary wires with a nominal voltage of 1500–3000 V DC and a power range of up to 12 MW for each train. The high train power and restriction on the number of operating trains because of the high currents taken from the overhead catenary system (OCS) made the experts think about increasing the voltage between 7.5 and 24 kV in the future. However, such systems are still under study and development.

9.2.2 AC RAILWAY SYSTEMS

With the high-power needs of HSR systems and the fact that MVDC supply still has a long way to be established, the medium voltage AC (MVAC) grid is a mature and popular technology adopted in these systems. MVAC-based HSR systems are

TABLE 9.2
Different Voltage Levels of AC ERSs

Maximum instantaneous voltage	Maximum permanent voltage	Nominal voltage	Minimum permanent voltage	Minimum instantaneous voltage	ERS voltage
18 kV	17.25 kV	15 kV	12 kV	11 kV	15 kV AC, 16.7 Hz
29 kV	27.5 kV	25 kV	19 kV	17.5 kV	25 kV AC, 50 Hz

the final category of ERS types, which have been implemented by 15 kV-16.67 Hz or 25 kV-50/60 Hz OCS and a power range up to 15 MW for each train. Suburban and HSR ERSs usually are closed to remote areas and motorways or highway lines. Therefore, the opportunity of utilizing the existing ERS installations in such areas for power supplying of establishing EVCSs can be a prominent advantage and feature that will be mentioned in the following sections. Depending on the supplying voltage level, AC ERSs can be classified into two groups, as shown in Table 9.2.

9.3 BACKGROUND OF ELECTRIC VEHICLE CHARGING INFRASTRUCTURES

Against the diversity of ERSs, which is summarized in Figure 9.1, EV charging infrastructures (EVCIs) also contain various levels that can be classified based on the power range, power distribution type, and standards. The five categorized groups of EVCIs illustrated in Figure 9.1 can be divided into two groups of low-power AC EVCIs and high-power DC EVCIs [2].

9.3.1 Low-Power AC EVCIs

This group of EVCIs provides EVs to be connected directly to a single-phase/three-phase AC grid due to the internal battery charger. Accordingly, they are utilized for an enormous installation of charging lots covering a wide spread of EVs. They are commonly used nowadays and equipped with a household socket (NEMA 5–15) with 120/240 V and around 32A with the standard. However, this category is characterized by low charging power (generally up to 22 kW). Thus, it is the basic level of EVCS and is known as a slow charging method (2–8 hours). They are appropriate for household applications or while the vehicle can stay stopped for a long time, at least a few hours.

9.3.2 High-Power AC EVCIs

These types of EVCIs are characterized by a high charging power due to the transfer of battery chargers from the vehicle inside to the charging station itself. In this

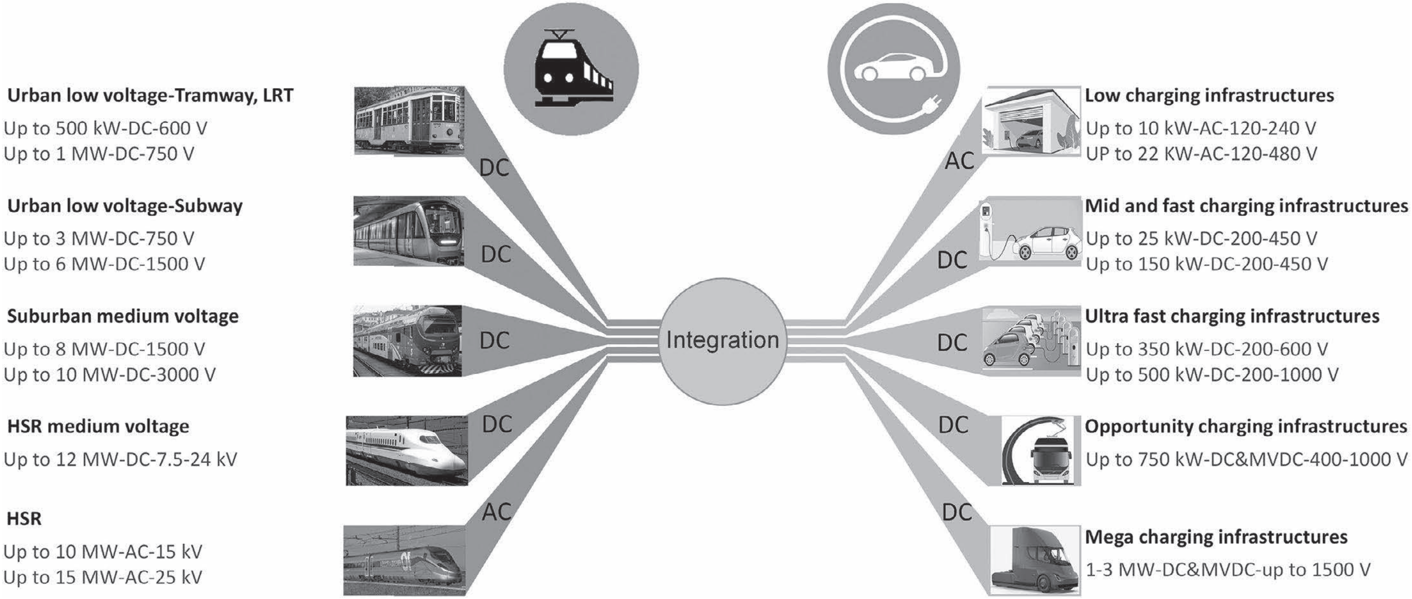


FIGURE 9.1 Different structures of ERSs and EVCIs.

context, the power electronic (PE) converter rating inside the charger can be enhanced because there is no limitation in terms of volume and weight. Nowadays, the EVCIs contain not only the control and protection units but also all operations related to the power appliances and converting and regulating the power from an AC three-phase system to the onboard DC batteries. The expense of these EVCIs is much higher than the AC types. Therefore, DC EVCIs are often used for reducing the charging time and are known as fast chargers. Furthermore, they are substantially established along the motorways to actualize the so-called electric corridors, such as electrified roads, which provide an EV to travel for long distances.

DC EVCIs can be utilized for various types of vehicles like cars, buses, trucks, and motorbikes. Accordingly, high-power EVCIs also can be divided into four categories.

9.3.2.1 Mid and Fast Charging Infrastructure

The next category is dedicated to the mid (up to 25 kW) and fast (up to 150 kW) charging infrastructure commonly used nowadays equipped with Combo 2 and/or ChAdeMO plug. These are able to charge most of the current EVs and all the upcoming ones, preferably with the Combo 2 connection as chosen by the European Union as the charging standard. Due to the low power value, it is desirable to consider their connection in the low-voltage DC section. These systems have to be able to charge vehicles equipped with batteries up to 1000 V. Mid charging infrastructures are suitable for a charging time of 1–2 hours, while fast charging is mainly used to reduce the charging time to half an hour.

9.3.2.2 Ultrafast Charging Infrastructure

Ultrafast charging infrastructure, typically up to 350–500 kW, is under development even if some real installations are already active. The main problems related to ultrafast charging infrastructures are their huge impact on the AC mains and the need for a water-cooled cable and connectors to handle high currents (up to 500 A). They are designed to reduce the charging time to the order of ten minutes, even if not all the EVs are able to accept so high a charging power. The presence of a high-voltage DC grid allows ultrafast charging infrastructure to reduce their impact on the mains and to directly use the connected renewable sources and the braking energy coming from the trains.

9.3.2.3 Opportunity Infrastructure

These systems are nowadays used for E-buses, even it is possible to use them for electric trucks. Their duty is to provide an intermittent short charge to the E-buses to extend their range in a working day. Since the connection to the vehicle is through a pantograph, the contact bars are able to handle a high amount of current, to reach a maximum charging power up to 750 kW. These systems can benefit from an MVDC grid for their supply due to the high amount of power required. Moreover, they contribute to promoting the use of public transport since they can be implemented in correspondence with the train stations facilitating intermodal mobility (train + E-bus).

9.3.2.4 Mega Charging Infrastructure

The next introduction of full-electric trucks and tractor-trailers from the main vehicle manufacturers will need the definition of new ultra-high-power charging infrastructures named mega chargers. These kinds of vehicles that are under development can be equipped with a 1000 kWh onboard battery. Accordingly, chargers in the order of 1–3 MW will be needed to reduce their charging time to an acceptable value.

9.4 INTEGRATION OF EV/E-BUS CHARGING INFRASTRUCTURES TO ERSS

The association of ERSs and EVCIs is an important action to reach sustainable transportation systems. Two perspectives can be considered regarding this integration. One is attaining intermodal transportation which regards the assessment of flexible connection of roads and railways considering appropriate integration in strategic points. It is mostly related to geographical and geopolitical investigations and is beyond the scope of this chapter. The other one, which is going to be discussed in the following sections, is the integration of power supply systems and charging infrastructures for both ERSs and EVs. Based on the ERSs' intrinsic characteristics, T2V/V2T integration perspectives can be evaluated and accomplished based on the following frameworks:

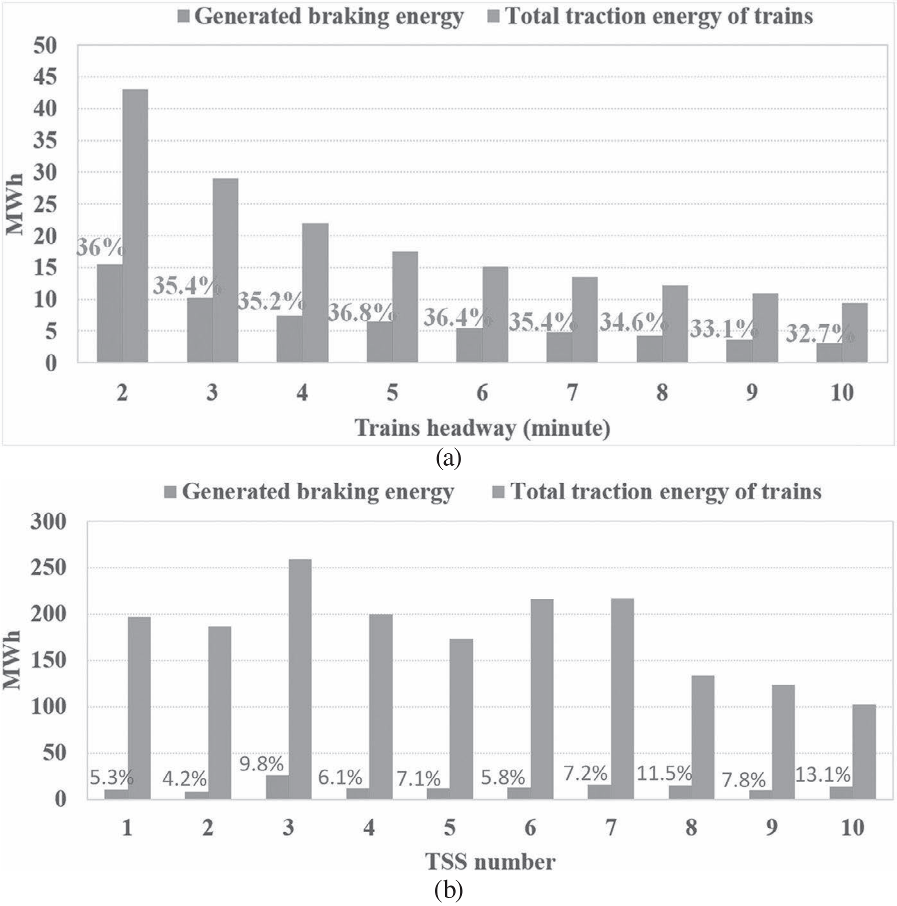
- Employing regenerative braking energy (RBE)
- Assuming EVs as stationary ESSs and distributed energy resources
- Utilizing the unemployed capacity of existing power installations
- Utilizing ERS lines as energy hubs preparing suitable connection areas for renewable energy sources (RESs)

9.4.1 INTEGRATION CONCEPT EMPLOYING REGENERATIVE BRAKING ENERGY

RBE as an indivisible feature of ERSs is a popular topic due to the significant effects on energy consumption depletion together with increasing system efficiency and sustainability. Today, most trains are equipped with an electrical braking system to not waste energy on rheostats. In this section, the potential of RBE to supply EVCIs and realize T2V technology will be discussed.

RBE rating and recovery methods in DC and AC ERSs can be varied. In DC systems, especially low-voltage types due to the lower voltage level, higher losses, and the proliferation of TPSSs, there are substantial impediments to recuperating. It is worth mentioning that, due to the line limitations and protection issues, all the recoverable RBE can't be recuperated. The recoverable RBE range for a typical metro line in Milan is measured as 32–36% and the total daily traction energy and RBE of the line for a typical timetable are calculated as 320 MWh and 145 MWh, respectively. The energy figure according to the headway of trains is shown in Figure 9.2a. It can be seen that by increasing headway time, the RBE rating is decreased because of the low number of trains and power losses during transfer between trains. In fact, with non-reversible TPSSs, the first priority to utilize RBE is to supply the other adjacent train in motoring mode. Even adopting the best optimization methods, a significant portion of RBE can't be utilized. The field measurements have demonstrated more than 25% of wasting RBE as heat in onboard rheostats in worse cases and more than 10% on average.

For AC ERSs, RBE production rate is also linked to train speed, train mass, total inertia, and braking duration. Furthermore, the total energy range in AC ERSs is much higher than DC ERSs. Accordingly, the production of RBE also in AC and high-speed ERSs is important and based on real measurements (as shown in Figure 9.2b) that can be in the range of 4–13%. For example, the total daily traction energy and RBE of an AC ERS line for a typical timetable are calculated as 1800 MWh and 138 MWh, respectively. It is obvious that even with the low percentage of RBE contribution, its quantity is high and almost equal to the daily amount of a DC metro line. Due to the neutral zones and phase differences for each section of TPSSs, transferring RBE from one section to the other is not possible and therefore in AC ERSs RBE is fed back to the primary side of TPSS. This returned RBE has many issues in terms of PQ, and



(a)

(b)

FIGURE 9.2 Trains' total required traction energy and recoverable braking energy. (a) In a typical 1500 V DC metro line. (b) In a 25 kV AC high-speed line.

the railway companies are reluctant to use it for internal consumption. Consequently, a suitable way to use RBE in AC ERSs has not been applied, and experts are looking for innovative technologies.

In addition to the ratings of RBE, evaluating its recuperating methods is also significant. The different solutions can be defined for RBE utilization in both DC and AC ERSs [3], which can be classified into meantime and storing-based methods. These approaches are listed in Table 9.3, and the detailed evaluation together with advantages and disadvantages are explained in [3]. Considering only the unused portion of daily RBE, which is lost as heat, and assuming the average battery capacity of each EV as 50 kWh, more than 280 EVs can be fully charged in a day.

It is obvious from the table that ESSs are popular for RBE management and can be utilized in larger sizes, providing high energy storage volume. However, the cost of implementing ESSs for each TPSS is too much. Accordingly, utilizing available dedicated batteries of EVs instead of establishing new stations can substantially decrease the costs and facilitate achieving sustainable transportation. To supply EVCIs by RBE, the features of demanded load and production must be evaluated. From the ERS side, the main issue of RBE is its impulsive and discontinuity production features. In fact, the electric braking of trains has high power in a very short duration. Depending on the ERS type and train specifications, the generated energy

TABLE 9.3
RBE Management Techniques Classification

		Method & Application	**ERS type**	
			DC	**AC**
Meantime methods		Supply other vicinity trains	✓	†
		Supply onboard auxiliary services	✓	–
		Send back to the primary grid/mains	‡	✓
		Waste by onboard rheostats	✓	–
Storing-based methods	Onboard	Supply onboard auxiliary services	✓	–
		Supply train in autonomous operation mode	✓	–
	Offboard	Supply stationary auxiliary services	✓	✓
		Supply accelerating trains	✓	–
		Supply track—emergency situation	✓	✓
		Supply track—peak shave/load shift	✓	✓
	Wayside	Supply track—emergency situation	✓	✓
		Supply track—voltage regulation	✓	–
		Supply track—peak shave/load shift	✓	✓
		Local distributed energy resource	✓	–

† In case of utilizing RPC in TSS or sub-sectioning posts

‡ In case of possible reversible substation

flux parameters can be varied. For instance, for low-voltage ERSs, the speed and inertia of the trains are lower than suburban and high-speed trains.

Therefore, braking time, peak power, and the value of RBE are smaller too. However, the frequency of braking is much higher due to the short headways between trains, which causes an RBE profile more like the continuous mode. Accordingly, management of RBE is more comfortable in low-voltage DC ERSs with respect to the other types. Based on what has been discussed so far, two scenarios as the meantime and ESS-based integration can be defined to supply EVCIs by the RBE of ERSs.

9.4.1.1 Meantime Integration of ERSs and EVCIs

The first mode of integration is the meantime type in which RBE will be transferred to EVCSs uninterruptedly. Figure 9.3 shows the proposed scheme related to this scenario. As mentioned before, one of the main issues in this mode is the mismatch between produced and consumed powers. The power of trains during the braking is in the range of megawatts, while the power required by EVs is in the range of several kilowatts. Thus, it is mandatory to have many numbers of EVs in the parking area or locate multiple EVCSs connected along the ERS line and work together to absorb and consume RBE in a high range. This method is suitable to be implemented around ERSs, which are nearby to the large EVCSs, such as business buildings and commercial centers with hundreds of available parking areas. According to the reports, the majority of vehicles approximately are parked for around 8 hours in such places [4]. Furthermore, the TPSSs close to the metropolis and motorways with a high volume of parking space are suitable for such an integration. The main challenge of the meantime scenario is the discontinuity of the braking energy production. It means that when trains are arriving at the station RBE will be available. Thus, in such a model, there should be an additional connection between the grid and EVCS (as shown in Figure 9.3). Considering a long time without RBE production, EVs can be charged directly through the grid via

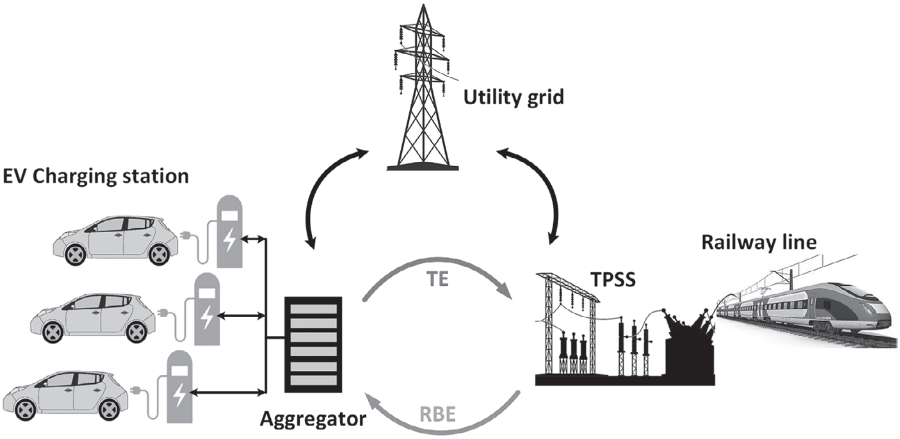


FIGURE 9.3 Scheme of meantime integration between ERSs and EVCIs.

grid-to-vehicle (G2V) technology. A precise aggregator should be implemented to evaluate the EVs' condition, with the available maximum charging rate to realize integration based on calculated prioritization [5].

9.4.1.2 ESS-Based Integration of ERSs and EVCIs

Given the fact that the majority of present EVCSs are in the small/medium range, the meantime integration scenario is not a suitable choice for implementation. Therefore, another indirect method can be introduced by utilizing ESSs as an auxiliary device between ERSs and EVs. Thus, the additional energy during braking can be stored on ESSs and when there is no RBE, EVCSs can be fed from the grid. This scheme allows the continuity of the power transferring, and absorbing RBE with the low number of EVs [6]. In comparison to the meantime method, there is no need for an additional connection with the grid. Figure 9.4 illustrates the scheme of ESS-based integration.

9.4.2 INTEGRATION CONCEPT ASSUMING EVs AS STATIONARY ESS AND DER

In the last section, transferring RBE from ERS to EVCI is discussed. Similarly, power flow from EVCI to ERS supplying traction energy (TE) of trains also can be realized by taking advantage of dedicated batteries inside EVs. The meantime power flow can be executed when trains are accelerating or during peak hours. In this way, by management of the aggregator, those batteries of EVs that are fully charged are participated to operate together as distributed energy resources and auxiliary supply ERS. Assuming the high number of participated EVs, a general power threshold (P_g) for EVCSs can be specified that is matchable with the accelerating

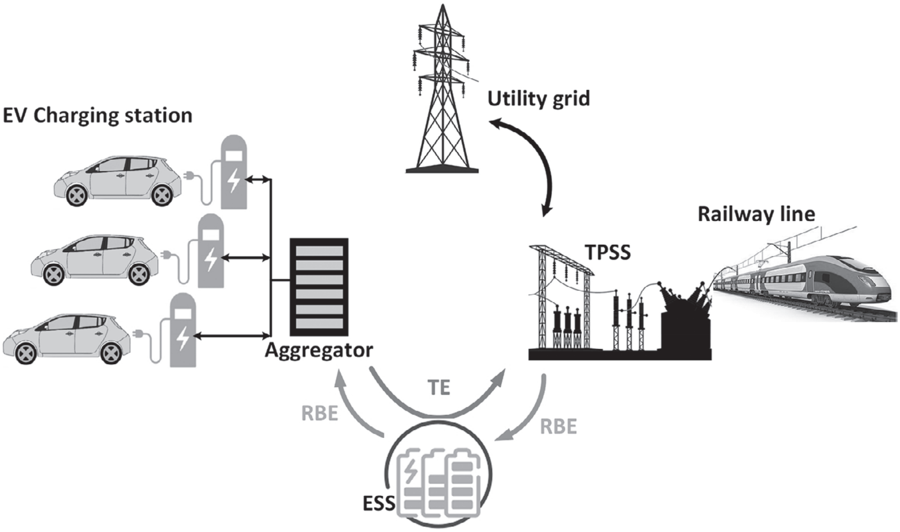


FIGURE 9.4 Scheme of ESS-based integration between ERSs and EVCIs.

traction power (P_{at}) of trains. In this mode, to completely supply the accelerating train, the following equation must be valid.

$$\begin{cases} \sum_{m=1}^{N} P_{d,m} \geq P_g \\ P_g \geq P_{at} \end{cases}, \tag{9.1}$$

where $P_{d,m}$ is discharging power rate and N is the total number of participated EVs. The amounts of P_{at} for each TPSS should be evaluated based on the average threshold powers of departure trains. From an EVCI point of view, the implementation of such integration depends on the number of EVs, the charging/discharging power rate of EVs, and their SOC. In case of insufficient EV number, ESS-based connection can be proposed, taking advantage of hybrid ESSs as an auxiliary device. Thus, during acceleration of trains or peak shaving intervals, ESSs collaborating with EV batteries can supply trains. Literally, ERSs can be supplied by cheaper energy through this integration since EVs are often charged by lower tariffs or RESs.

9.4.3 INTEGRATION CONCEPT UTILIZING THE UNEMPLOYED CAPACITY OF EXISTING POWER INSTALLATION

The power rating of ERSs and equipment is determined based on the line information and the peak power related to the rush hours. Generally, the designed and installed capacity of TPSSs are assigned more than the required operating capacity. Therefore, the significant capacity of ERSs and dedicated equipment are not employed and are available for long intervals during the day, which can be utilized to charge EVs. Using existing ERSs and installations to supply the EVCIs will substantially decrease the operating costs. In order to explain it more clearly, the power profile related to some of the Milan tram substations is evaluated. The daily power profile of six TPSSs that supply the tramway line is illustrated in Figure 9.5. It must

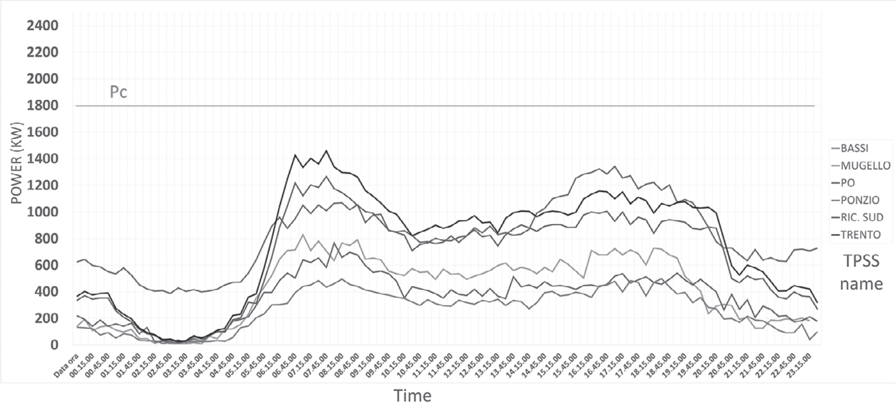


FIGURE 9.5 Daily power profile for Milan tramway substations.

be noted that each TPSS possesses 2500 kW maximum power capacity. Considering the yearly power profile, the suitable contracted power (P_c) can be assigned as 1800 kW, which is indicated by the dashed red line in the figure. Comparing the power profiles with P_c, it can be concluded that a large amount of the existing capacity of the tramway system and its installations are unemployed, which can be used to supply EVCIs. It is worth mentioning that a suitable optimized threshold for P_c is important and will lead to the optimum energy consumption invoice. Adopting the energy stored in EVs to operate the peak-shaving function of traction substations can significantly decrease P_c for ERSs.

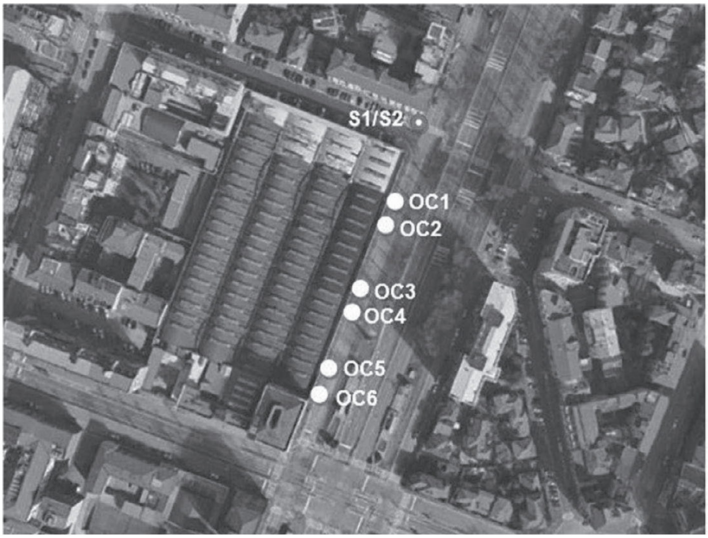
One practical example of the pioneering projects regarding this T2V framework has been implemented on Zara Street in Milan, Italy [7], where E-bus opportunity chargers are integrated and supplied by tramway charging lines. The proximity of both an E-bus charging infrastructure and tramway lines at this location (as shown in Figure 9.6) has increased its operational potential.

9.4.4 INTEGRATION CONCEPT UTILIZING ERS LINES AS ENERGY HUB PROVIDING SUITABLE CONNECTION AREAS OF RESs

Regarding the EU climate commitment assigned purpose, attaining a zero-carbon eco-friendly transport system by 2050 has become the main objective in the field of transportation. In this way, the integration of renewable energy sources (RESs)

(a)

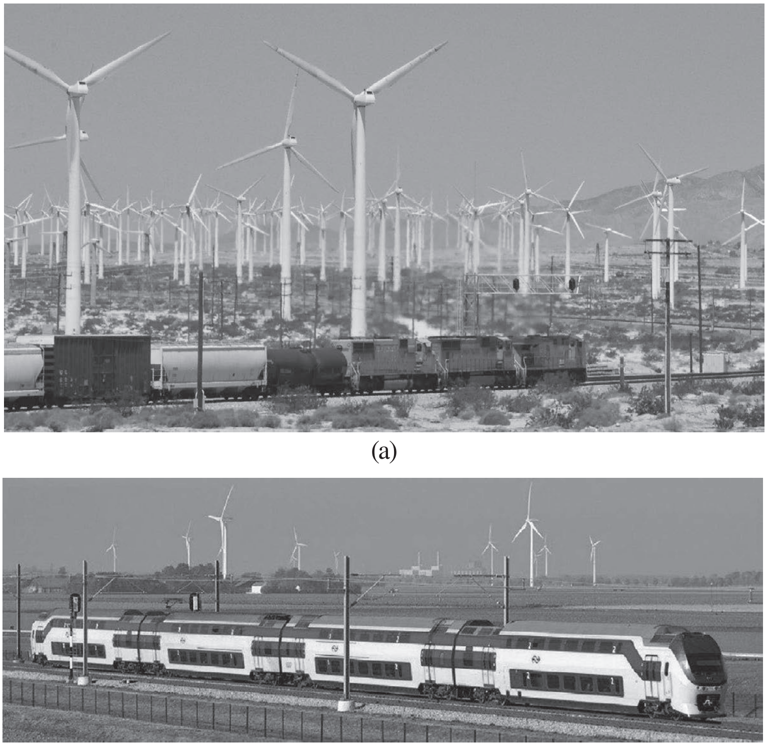
FIGURE 9.6 Integration of E-bus opportunity charging station to tramway's DC grid in Milan, Zara Street.



(b)

FIGURE 9.6 (Continued)

with existing electric transportation, can be an important step. In recent years, numerous research has been accomplished regarding the integration of EVCIs and RESs, but the development of such an integration in ERSs is insufficient. However, ERSs have a high potential to be integrated with RESs because of widely distributed lines all over the regions that are closed to wind farms or PV plants. Figure 9.7 demonstrates two real locations in which ERSs are close to the wind farms [8,9]. In other words, using the existing installations and supply lines of the ERSs, the power flow between RESs and loads can be facilitated [10,11]. This is not limited to the lines, but also at railway stations. Due to the large area of stations, the roofs are the best place to install PV panels in addition to trackside PV panels. Based on the report of the Indian Ministry of Railways, 111 MW of solar power capacity has already been installed on rooftops of different stations in January 2021 [12]. Figure 9.8a demonstrates a picture of an Indian railway substation with PV panels. This country is a pioneer moving toward net-zero carbon emission railway systems. Meanwhile, Japan Railway East plans to replace about 20% of the total electricity used in railway networks supplied by RESs, including wind and solar power [13]. Figure 9.8b shows a Tokyo Station Tokaido line platform where PV panels with 453 kW capacity have been implemented. Overall, the concept of ERS and EVCI integration in this framework can be addressed by acting as an energy hub. In other words, for the realization of such an integration, the distributed railway lines act as an energy hub and transfer energy between traction substations and EVCSs. Consequently, both systems can take advantage of RESs.



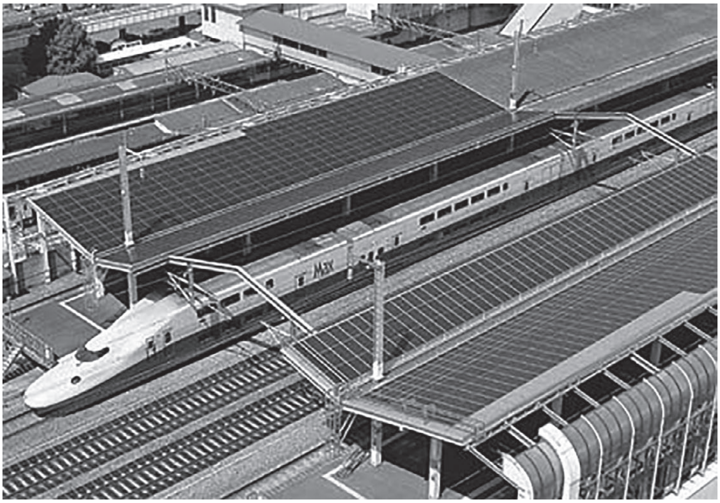
(a)

(b)

FIGURE 9.7 The proximity of ERSs and wind farms. (a) One of the largest wind farms in California called San Gorgonio Pass [8]. (b) H1S railway line in the UK [9].

(a)

FIGURE 9.8 Rooftop PV implementation in railway substation. (a) India substation [12] (b) 200 and 400 kW PV panels on the roof of Takasaki-Tokyo stations in Japan in 2004 [13].



(b)

FIGURE 9.8 (Continued)

9.5 DIFFERENT ARCHITECTURES OF ERS AND EVCI INTEGRATION

In the previous sections, various frameworks for ERSs and EVCIs were explained. The outstanding features and benefits of such an integration motivated the authors to study and analyze the different aspects of incorporating RESs. In this section, different structures of integration considering DC and AC systems and the concept of an energy hub will be explained.

9.5.1 Low-Voltage DC Hub-Based Integration

DC ERSs are mostly low-power systems localized in metropolitan and urban zones with a large population. The dedicated supplying DC lines for these systems are distributed throughout the city. On the other side, the majority of DERs are based on DC networks, such as PV and ESSs, or they contain a DC part inside, like wind generators [2]. Meanwhile, mid and fast EVCIs with DC-type charging systems are distributed places close to railway lines or stations. This similarity can increase the interconnection possibility. The general concept of T2V/V2T integration in low-voltage ERSs is shown in Figure 9.9. LVDC ERSs (0.6–1.5 kV), are usually used in urban rails, trams, light rails, and subways in low/medium distances and are known as low-power transportation systems. Accordingly, low-power elements can be integrated with such a system. In this architecture the shared DC busbar as an energy hub and integration place can be implemented in two positions: substation location and along the line. Substations are the most appropriate place since there are existing switching and protection devices together with buildings that can be shared for new connections. Furthermore, the proximity of the AC mains provides greater power transfer. For the along line position, the integrations can be more complex but provide supplying EVCIs in strategic points, such as parking lots near railway stations.

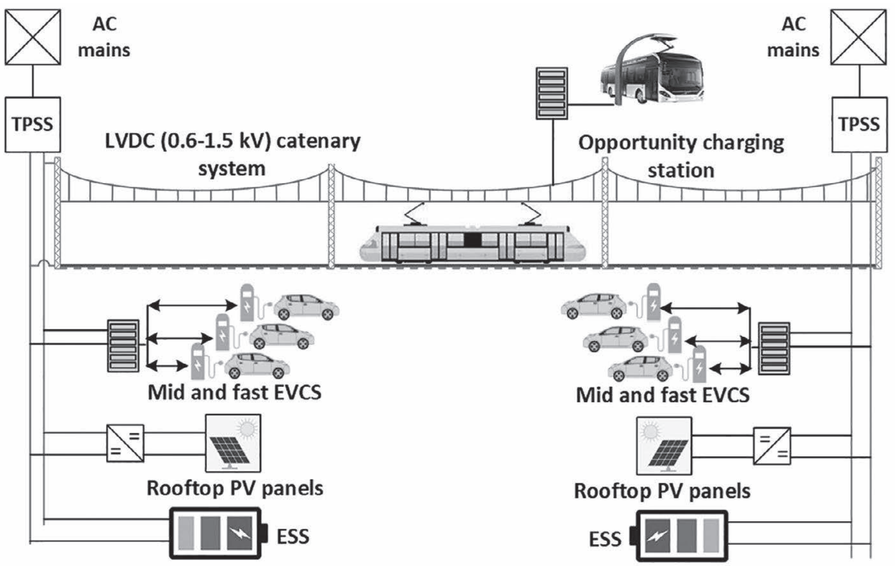


FIGURE 9.9 T2V/V2T integration architecture in LVDC ERSs.

RESs that can be connected to LVDC architecture are in the class of low-power generators, such as small-scale PV plants or low-power wind generation. However, due to the lack of empty space or its high cost in cities, the suitable choice seems to be rooftop PV panels implemented in substations. The outstanding specification of this architecture is the direct connection of EVCIs to DC bus due to the proximity of the voltage levels. Despite the fact LVDC architecture is not appropriate for mega chargers and ultrafast charging systems, it will be effective for mid/fast charging systems, which mostly use and are equipped with Combo or Chademo plugs. In addition, as mentioned in previous sections, opportunity charging systems for E-buses can be easily integrated without an interface in this architecture.

In order to realize T2V/V2T technology more efficiently, hybrid ESSs also can be implemented in DC bus, which can collaborate with EVs to handle the power peaks of railway substations.

9.5.2 MEDIUM-VOLTAGE DC HUB-BASED INTEGRATION

As mentioned before, LVDC ERSs suffer from a low power rating, which can affect the number of operating trains. Therefore, for suburban and HSR lines with high-power demand, a higher voltage is required. Motivated by the PQ-based issues of AC ERSs, the experts are working toward modern medium-voltage DC (MVDC) ERSs with high-power ability. The high-power capability of MVDC ERSs simplifies the direct connection of RESs, such as high-power wind and PV generation. From an EVCI point of the view, MVDC architecture can provide the realization of ultrafast (up to 500 kW) and mega charging stations (in the order of 1–3 MW) which could be troublesome if they are connected to the AC utility grid for their power consumption range. On the other side, OPCSs that provide an intermittent short charge to

E-buses can take advantage of MVDC architecture, reaching a maximum charging power up to 750 kW. Figure 9.10 demonstrates the architecture of MVDC ERSs integrated with RESs and EVCIs. In this architecture, the high-power elements can be connected directly, but low-power elements, such as small PV generators and mid or fast EVCIs, require some DC/DC converter. In some suitable nearby positions, MVDC ERSs can also supply LVDC ERSs independently or even supportively. In fact, MVDC ERSs can incorporate LVDC ERSs via suitable DC/DC converters. Similar to the LVDC ERSs, the MVDC shared bus can be implemented in two various positions of substation and along the line.

9.5.3 AC HUB-BASED INTEGRATION

Despite the many advantages of MVDC ERSs, they require a lot of time to be developed and expanded. Therefore, the alternative choice to have high-power railway lines is utilizing AC ERSs, which now are mature technology.

However, these systems are implicated by significant PQ issues that necessitate the existence of additional compensators. On the other side, in such a system, transferring RBE between trains is less likely because of the neutral sections and unlike the LVDC ERSs, it is possible to return it to the utility grid. Such a system refers to AC ERSs. Accordingly, the implementation of T2V/V2T technologies in such a system required some limitations. The general concept of integration in AC ERS is demonstrated in Figure 9.11. This architecture contains traction transformer-based substations with

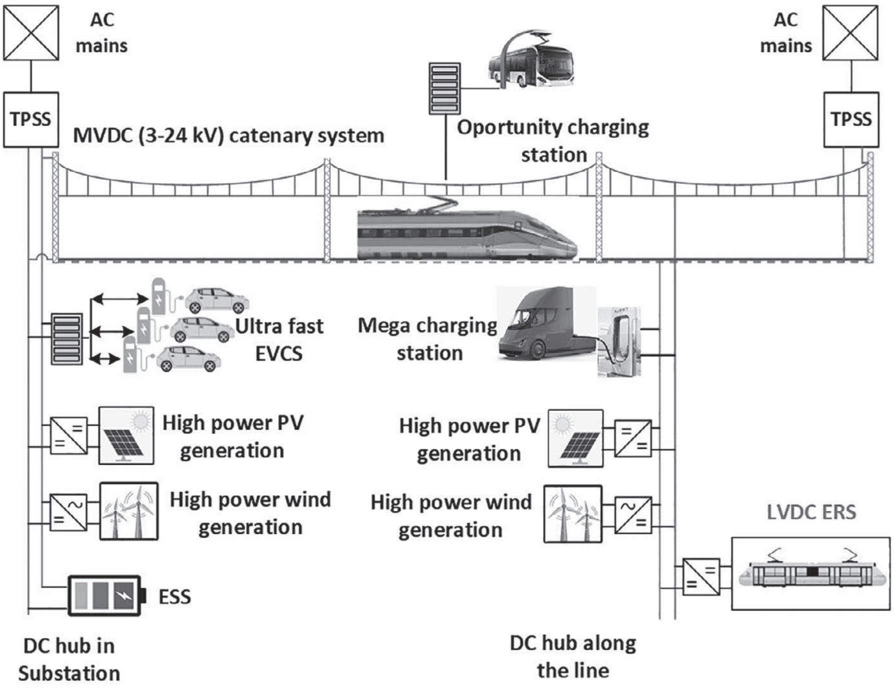


FIGURE 9.10 T2V/V2T integration architecture in MVDC ERSs.

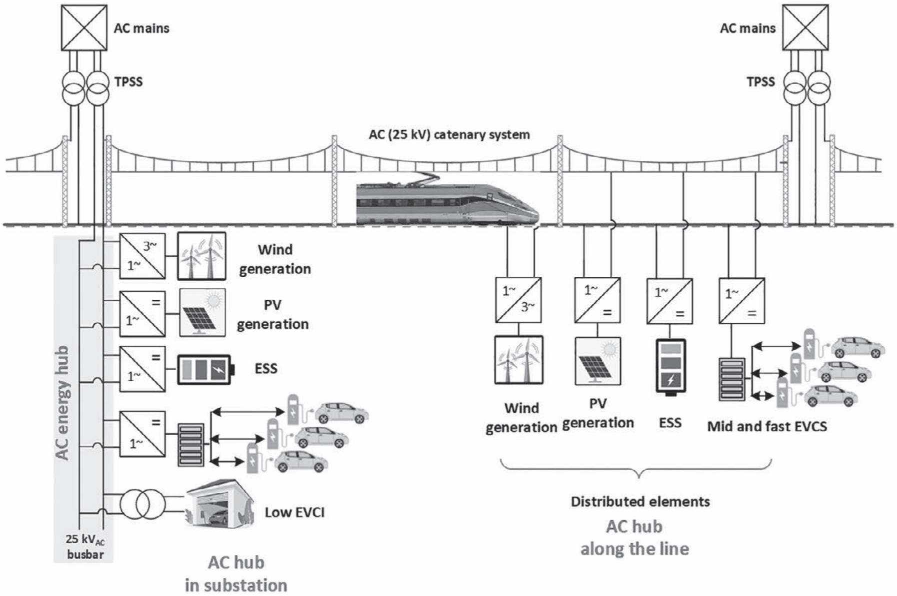


FIGURE 9.11 T2V/V2T integration architecture in AC ERSs.

25 kV OCS separated in an insulated area. The joint AC bus as an energy hub can be implemented in two various formats: concentrated in the substation or distributed along the line. In this architecture, elements are mostly integrated into the AC hub through DC/AC converters. Avoiding PQ issues relating to the switching frequencies of such converters, the power flow capacity must be lower. Consequently, RESs connected to AC ERSs are in the low-power range. From an EVCI point of view, the low-power features of such a structure may not be suitable for mega chargers or even ultrafast charging systems. However, the integration of mid and fast EVCIs through special rectifiers and low EVCIs through step-down transformers can be realized. It is worth mentioning that the integration of elements through the rectification process can intensify PQ issues in AC ERSs.

9.5.4 HYBRID HUB-BASED INTEGRATION

To overcome the problems of AC-based architecture and increase the power-flow capacity, a hybrid configuration can be proposed. In hybrid architecture, taking advantage of a high-power interfacing device (different kinds of interface converters or compensators [14]), a joint DC bus can be established to facilitate the connections of elements. Depending on the interface device, various configurations can be proposed for hybrid architecture, which is explained in detail in [2]. The scheme of hybrid architecture for T2V/V2T integration is shown in Figure 9.11. Interface converter can create an increased bidirectional power flow between AC and DC buses. The high-power capability of hybrid architecture allows the direct connection of high-power RESs. Meanwhile, from an EVCI point of the view, this system can provide the

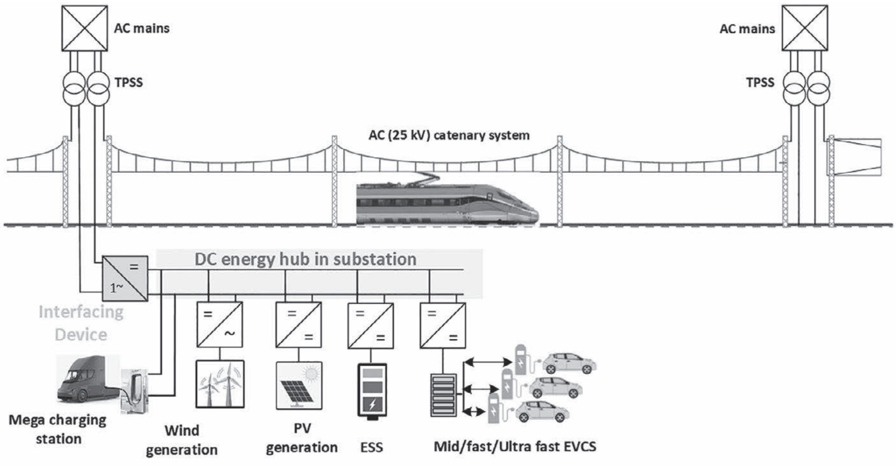


FIGURE 9.12 T2V/V2T integration architecture in hybrid ERSs.

realization of mega EVCIs, which could be problematic in the AC architecture. It must be noted that during busy times with high consumed loads if all the elements work at their full rates, the suitable control interface device, and consequently PQ controlling, will be very complicated. Due to the high cost of implementing DC bus along the line, this architecture it is better to be realized in the substation position.

9.6 MODELING AND INTEGRATION IN MVDC-BASED ARCHITECTURE

In order to realize the integration architecture mentioned in previous sections, modeling of such an integration in MVDC ERSs is discussed in the present section. As mentioned, RESs will play a crucial role in the power supply of ERSs and the feasibility of this integration to ERSs, especially for high-speed railways, is under scrutiny in order to evaluate the technical and economic aspects of such an idea. This section presents an example modeling on the integration of wind turbines (WT) and photovoltaic (PV) as auxiliary power supply to an MVDC railway microgrid together with the concept of T2V and V2T. Thus, power electronic converters are the key factor for the integration. Accordingly, the layout of the proposed MVDC ERS will include the following:

- TPSS connected to the main high-voltage AC through step-down transformer and AC/DC converter in order to convert the AC to DC;
- Catenary system that connects all the units, including TPSS, ESS, RES, and charging infrastructure;
- RESs, including WT and PV, connected to the catenary system through AC/DC and DC/DC power converters;
- ESSs, including batteries and ultra-capacitors, connected to the catenary system through DC/DC converter; and

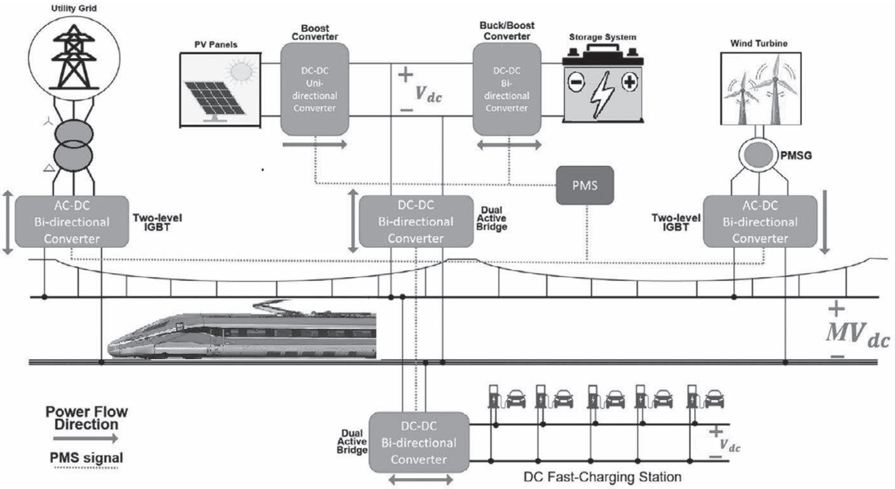


FIGURE 9.13 Proposed MVDC railway microgrid system architecture.

- Charging infrastructure, including mid/fast charging stations, ultrafast chargers for EVs, opportunity charging, and mega chargers for trucks, connected to the catenary system through DC/DC converters.

A simple example of the proposed MVDC system is shown in Figure 9.13. It includes two RESs (one PV plant and one wind farm) and an ESS unit. The grid supplies the catenary system through TPSS, and the EV fast charging station is integrated through a DAB converter along the line. PV panels and ESS are integrated using dedicated DAB-based power electronic converters. DAB converters support bidirectional power flow between the MVDC catenary system and the other connected components. Meanwhile, EV fast charging infrastructure connection via a DAB converter can provide the system bidirectional power flow to realize the G2V and V2G technology.

9.6.1 INTEGRATION OF PV PANELS

The PV system includes panels and a boost converter for maximum power point tracking (MPPT) purposes. Generally speaking, a large range of DC/DC power converters can be implemented to connect the PV farms to the MVDC railway system. For instance, non-isolated soft switched interlocked boost (SSIB) DC/DC converter, modular cascaded DC/DC converter, hybrid resonant PWM, full-bridge DC/DC converter, or phase shift full bridge (PSFB) DC/DC converter can be applied. Nevertheless, the choice for the final step DC/DC converter is a DAB converter due to its galvanic isolation, soft switching, etc. However, for simplicity, a boost converter has been modeled to connect PV to the MVDC system in this chapter. Because of the changing features of solar radiation and temperature, the output power of PV is variable. Consequently, the MPPT algorithm is adopted to guarantee the maximal power extraction. Different MPPT algorithms, including perturb and observe (P&O),

incremental current, artificial intelligence (AI), etc., are presented in the research. The selected method in this chapter is P&O due to its simplicity and feasibility. The concept of the P&O method is shown in Figure 9.14. It is clear that in this method the PV output voltage changes with the small variation of irradiance. It modifies the output power of the PV system illustrated with ΔP. Its principles are described as: If ΔP > 0, it reveals that it is getting close to MPP, and therefore, any increment in the same direction will move the operating point toward MPP; If ΔP < 0, it presents that the operating point moves away from MPP, thus its direction must be reversed.

9.6.2 INTEGRATION OF WIND TURBINES

Wind speed and wind turbine (WT) diameters are two major determining factors of output power; as the turbine's blade diameter increases (larger turbines), the turbine will capture a higher level of wind power that will consequently be more efficient compared to turbines that are connected in a different manner. Different types of WT can be addressed and elaborated traditionally and at the commercial level; AC WT can be connected in various configurations that can be then connected to an MVDC railway system through AC/DC power electronic converters. However, due to the development of direct current (DC) power transmission, implementing DC WT can be advantageous in comparison to traditional AC WT. The principal requirement of such an idea is developing DC WT, which is just at the incubator of the research phase, but all details of both technologies will be elaborated to have a better insight into the future of the MVDC

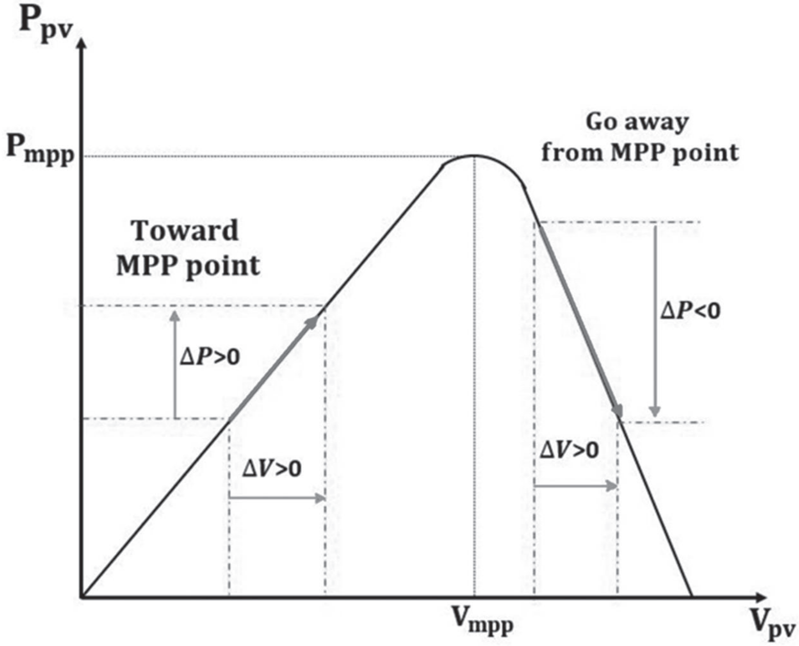


FIGURE 9.14 MPPT working principle.

railway system inherited RESs. The other main objective is to select an optimum point that has the highest mean wind speed during the year and is close to the railway in order to avoid any cable losses. Accordingly, the designed parameter is not considered in this chapter. In this context, a permanent magnet synchronous generator (PMSG) is adopted connected with the DC catenary system using an AC-DC power converter.

For low-power generation, a diode rectifier plus DC-DC converter is utilized, whereas in high-power purposes an active PWM rectifier is utilized. The dynamic relationship of a PMSC is as follows:

$$\begin{cases} V_{sd} = -L_q p\omega_r i_{sq} + L_d \dfrac{di_{sd}}{dt} \\ V_{sq} = p\omega_r \varphi_v + L_d p\omega_r i_{sd} + L_q \dfrac{di_{sq}}{dt} \end{cases}, \tag{9.2}$$

where (i_{sd}, i_{sq}) and (V_{sd}, V_{sq}) are the DQ coordinates and (i_{sa}, i_{sb}, i_{sc}) and (V_{sa}, V_{sb}, V_{sc}) are of the ABC coordinates of stator current and voltage, respectively. p is the number of pole pairs, φ_v shows the magnetic flux linkage, and ω_r is the rotor angular speed. The WT generator with its control diagram is illustrated in Figure 9.15.

9.6.3 INTEGRATION OF ESSs

In the proposed MVDC ERS, storage systems are mainly needed to handle the power peaks that come from trains, both in traction and in the braking phase, and from RESs, especially from wind generators. In this way, it is possible to minimize the impact on the AC mains and the sizing of the AC/DC substations. The development of energy

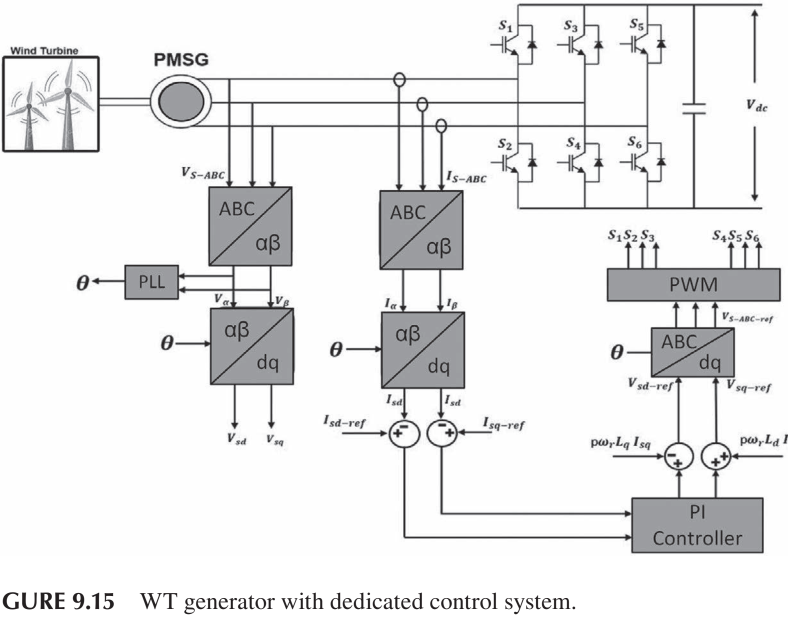


FIGURE 9.15 WT generator with dedicated control system.

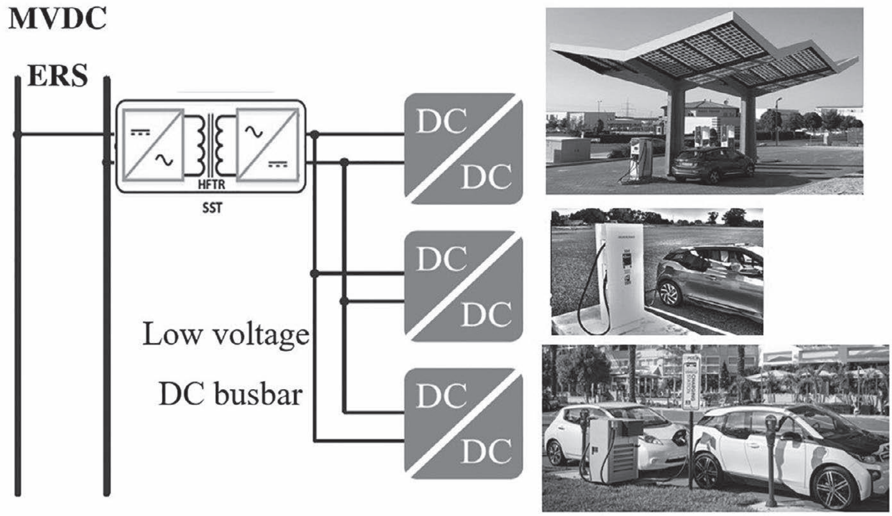
consumption and efficiency includes extra advantages for the ERS's operator and for the electric system in general. In designing ESSs and determining their suitable size for smart ERSs, two main subjects needed to be studied: the RBE level in relation to the railway traffic and the amount of installed renewables. In the ERSs, storage systems can save train RBE and handle the power peaks that come from trains and renewable sources. Therefore, the high-density ESSs are applied as supercapacitors and batteries. The ESSs in MVDC systems can be divided into three types: onboard, offboard, and wayside [3]. The onboard ESS is applied inside trains or even on the roof. Despite the advantages of lower loss and better saving of energy, the higher weight of onboard ESS can enhance the consumed power of trains and decrease speed and efficiency. The offboard ESS is commonly employed in substations. Besides the advantages of onboard ESS, the offboard ESS can supply the auxiliary and internal loads of substations, i.e., the lighting, air conditioning, and escalator. As mentioned, the limitations of size and weight have presented an obstacle to the application of onboard ESSs in ERSs. Moreover, the intersections of railway networks and RESs are propitious to the utilization of local renewable energy. Therefore, increasing the utilization rate of RBE and RES via ESS helps achieve the energy-saving goals more effectively.

9.6.4 Integration of EV Charging Infrastructures

To integrate the charging infrastructures into the DC catenary system of the ERPS, the following two architectures applicable for both low- and high-power charging stations can be proposed.

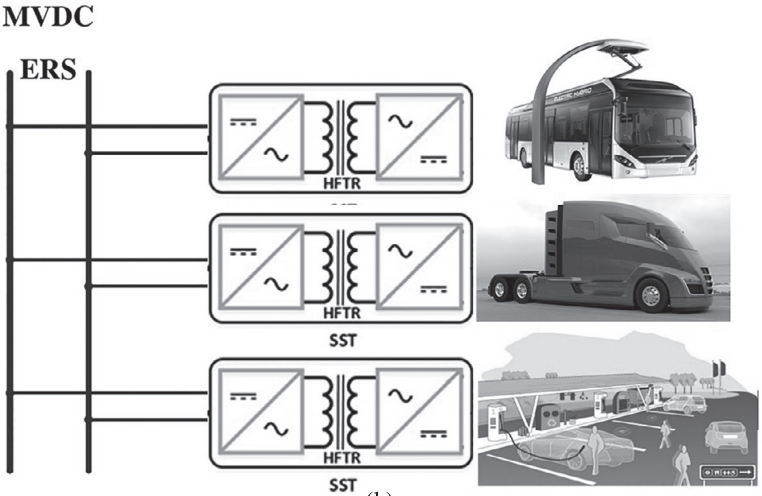
9.6.4.1 Two-Stage DC Charging Infrastructures

As it is shown in Figure 9.16a, the two-stage chargers are applicable for low-power purposes, where the first-stage solid-state transformer (SST) as a DC-DC converter



(a)

FIGURE 9.16 Integration configurations. (a) Two-stage charging station. (b) Single-stage charging station.



(b)

FIGURE 9.16 (Continued)

is isolated and interlinks the DC catenary system with the charging station. The second-stage DC-DC converter can be chosen to be isolated or non-isolated, and it is mainly installed to be able to charge various types of EVs with different voltage requirements.

9.6.4.2 Single-Stage DC Charging Infrastructures

The architecture of a single-stage charging station can be seen in Figure 9.20b in which one power electronic converter is directly interlinking the DC catenary system with various types of chargers, including mega chargers for E-buses and E-trucks. In this type of charger, the single power electronics converters are isolated in order to provide the system with galvanic isolation for meeting the safety factor. As mentioned, most EVs, E-buses, and E-trucks are compatible with various ranges of voltages. However, for the proposed integration, a charging infrastructure is connected to the MVDC catenary system. Also as mentioned, for connecting the charging infrastructure to the DC catenary system of the ERPS, an isolated power electronics converter is required. There are many choices for selecting the isolated DC-DC converter by considering its advantages and disadvantages. A dual active bridge (DAB) converter and phase shift full bridge (PSFB) converter are the most promising options due to their maturity and availability. For modeling the proposed system, a DC EV fast charging station is considered to be integrated with the smart DC catenary of the ERS via a DAB converter. The structure together with its control structure is shown in Figure 9.17.

A DAB converter consists of two single-phase full bridges and a high-frequency transformer (HFT). It transfers the energy from the DC catenary line to the EV's internal battery (and contrariwise in the case of V2G) using phase shifting. Changing the rate of phase-shift between the primary and secondary side converter, the DAB manages the power flow. The control function can be expressed as (9.3)

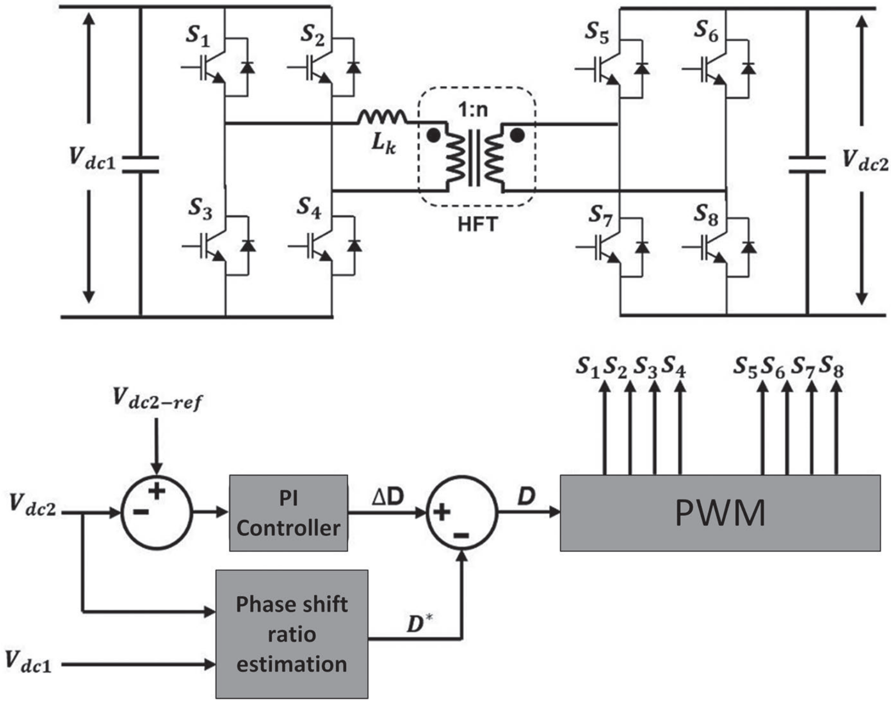


FIGURE 9.17 EVCI integration through a DAB converter and its control system.

$$P = \frac{V_{dc1} V_{dc2} \varphi (1-\varphi)}{n \pi L_k \omega}, \tag{9.3}$$

where V_{dc1} and V_{dc2} are the primary and secondary DC voltages, n is the turns ratio of primary and secondary windings of the HFT, ω is the angular frequency, L_k is the leakage inductance of the HFT, and φ is the phase-shift amount. The amount of phase shift and leakage inductance can be calculated as follows:

$$\varphi = \frac{\pi}{2}\left(1 - \sqrt{1 - \frac{8 f_s L_k P_{out}}{n V_{dc1} V_{dc2}}}\right) \tag{9.4}$$

$$L_k = \frac{V_{dc1} V_{dc2} d (1-d)}{2 f_s n P} \tag{9.5}$$

In (9.4) and (9.5), *fs* is the switching frequency and *d* is the duty cycle percentage. This type of converter can provide the system with galvanic isolation and the zero-voltage switching (ZVS), which decreases the losses and enhances the efficiency. To switch DAB, there are multiple phase-shifting methods, such as single-phase shift, dual-phase shift, triple-phase shift, extended phase shift, and hybrid phase shift. In this scrutiny, a single phase-shifting angle is chosen.

9.6.5 CONTROL MANAGEMENT SYSTEM AND RESULTS

The proposed MVDC system is simulated by MATLAB/Simulink software with real daily profiles as input data and assuming various working situations. To control the proposed system an energy management system or power management system (PMS) can be applied to manage the power flow between loads and sources. PMS is a centralized system that collaborates with the other decentralized units. As inputs, 24-hour real profiles of electric railway power demand at a specific TPSS, wind speed, solar radiation, temperature, and EV charging station power demand are applied.

The EV charging station is assumed in the suburban area where the EVs get charged during working hours and the peak hours are during the morning when the EVs arrive. The daily power profile of the EVCS is illustrated in Figure 9.18, which confirms that the peak hour happens from 7 a.m. to 11 a.m. To simulate the exact behavior of MVDC ERS, generating/demanding powers at one 30 MW TPSS is assumed. Figure 9.19 shows the daily power profile of a typical and middle TPSS in a bilateral MVDC line.

The uncertainty and time-varying specifications of ERS are obvious in this figure. During the night and early in the morning the passenger trains are not working and only freight trains are in operation. Therefore, the amount of required power is low.

The nominal power of the PV system is considered 3 MW, and the nominal output power of WT is 6 MW. The maximum output power demand of the EVCS is 500 kW,

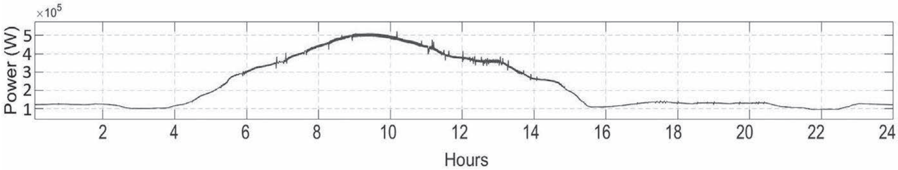


FIGURE 9.18 Fast charging daily power demand [10].

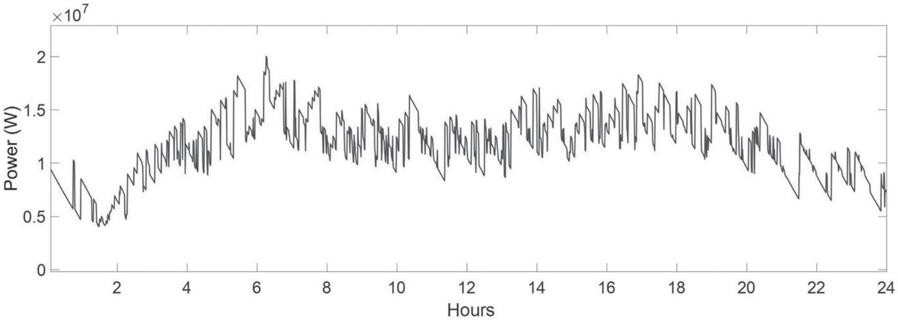


FIGURE 9.19 TPSS daily power profile.

which usually happens during peak hours. However, as is shown in Figure 9.19, the power demand of TPSS differs from 4 MW during off-peak hours to about 20 MW during peak hours. The features of the different parts of the proposed MVDC system are mentioned in Table 9.4.

Figure 9.20 demonstrates the daily voltage profile of the proposed catenary system, which remains on 9 kV DC with a +10% and −10% threshold, which is the acceptable range in ERSs.

For normal working condition, the power grid is the main supplier of the proposed MVDC ERS system. However, for emergency or some other situations, standalone mode can be executed too. Figure 9.21 illustrates the power profile of various elements in the proposed MVDC micro-grid, including the main grid, EVCS, RESs, and the ESSs. As it is clear, the proposed system is functional in the multiple working modes specified in the dedicated PMS. During night, the ERS's power demand is low and therefore both grid and WTs (if available) supply the loads. This mode is called feeding mode (FM). However, during the mornings and peak hours, thanks to RESs, it can be seen that peak-shaving mode (PSM) has happened. Therefore, the power supplied from the main grid is lower than the required power of loads by about 30%. For the rest of the day (from 7 a.m. to 8 p.m.) the proposed system is mostly working in the FM and the wind/PV/grid system can feed the loads (EVCS and trains). In some situations, if the SOC of the storage reaches 100%, and RESs

TABLE 9.4
Proposed MVDC System Parameters

System type	Feature
PV	14250 modules-1Soltech 1STH-215-P, 25 series+5750 parallel, 3 MW
WT	PMSC, 6 MW, 8 m/s (basic speed)
ESS	500 V, 4500 Ah Lithium-ion, 1s response time
EVCS-DAB	800 kW, 10 kHz switching frequency
TPSS	50 MVA, 4500 V AC, 50 Hz, 9 kV DC

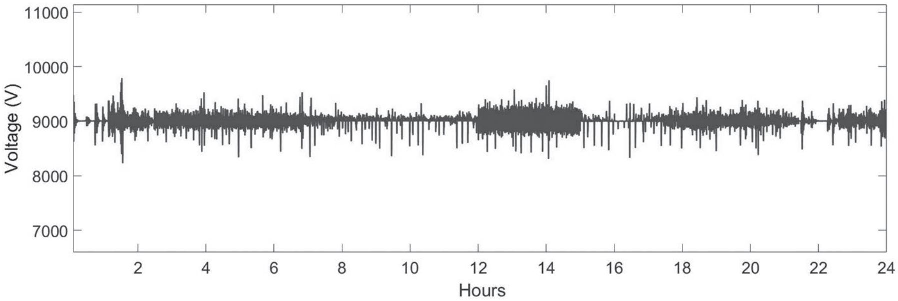


FIGURE 9.20 Voltage profile of the 9 kV catenary system [10].

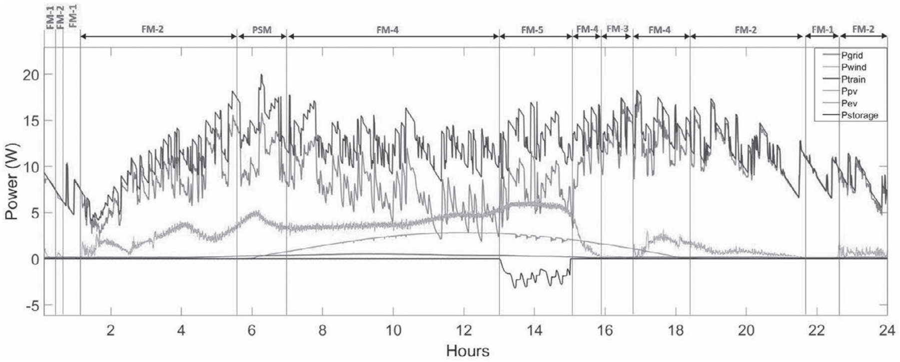


FIGURE 9.21 Power values for different sources and loads [10].

produce power, the additional power will be transferred into the main power grid, which illustrates recovery mode (RM). The results reveal that the proposed MVDC micro-grid system can be a promising solution to reinforce the ERSs feeding line for future and high-traffic issues. Consequently, introducing RESs, ESSs, and EVCIs and integrating them with existing ERSs can enhance system power capacity and efficiency. Meanwhile, it can compensate voltage drops and make smoother voltage profile on the overhead catenary.

9.7 CONCLUSION

Expanding and increasing EV/E-bus charging infrastructures in recent years may overload the utility grid and require new energy production and installations. The integration of ERSs as existing high-power networks with EVCIs can be a good solution to overcome the mentioned problem. In this chapter, the new concept of V2T/T2V technologies are introduced and different integration features are discussed, utilizing intrinsic features of RBE in ERSs. In addition, exploiting ERSs' dedicated lines as an energy hub to provide suitable connection areas with RESs is explained and different integration architectures for DC and AC ERSs are demonstrated. It is revealed that an MVDC-based architecture can provide both the advantages of the AC and LVDC types. A simple model is simulated to reveal the effectiveness of such a system. However, in the route of development of this architecture and despite the numerous advantages stated for the T2V/V2T integration, some challenges can be posed, especially the complexity of the smart control system and the high cost of PE-based modules and converters to evaluate its feasibility attentively for future executions.

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