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Electrical railway power supply systems: current situation and future trends

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Abstract— Railway electrification is experiencing a very important transformation process today. The need of increasing its capacity has evidenced the drawbacks of conventional systems of dealing with the higher power required, whilst maintaining reasonable costs. Furthermore, the current trend undertaken by electrical systems towards smarter grids involves to rethink carefully the direction of evolution of these systems. However, the different technical progress at the time of railway electrification, and the particular historical and economic characteristics of the countries, have led to a great variety of configurations that require different solutions. The first main objective of this article is to classify and describe the principal electrical railway power supply systems existing and the most important proposals for their improvement found in the literature. The second main objective is to make a comparison of all presented systems based on economic and technical criteria capable of assessing their suitability and future projection. The right choice of the feeding system is decisive for the development of more competitive, efficient and reliable railway systems.

Index Terms*— Electrical railway power supply system (ERPSS), transformer-based ERPSS, converter-based ERPSS, balanced transformers, converter conditioner, advanced AC converter-based ERPSS, advanced DC converter-based ERPSS*

1. Introduction

The current transportation system proves to be unsustainable [1] from the environmental, social and economic point of view. Among land-based means of transport, electrical railway is perhaps the most efficient, cleanest and safest of all. These features make it one of the key elements in the future transportation systems [2].

The progress of electrical railway power supply systems (ERPSS's) have been always much related to the technological advance available at the time. At the dawn of railway electrification, the utility grids were smaller and weaker than today, and the use of large motors at the industrial frequency presented a lot of inconveniences. All this led to the development of the direct current (DC) and the single phase low frequency alternating current (AC) dedicated systems as the best possible solutions.

With the subsequent progress of the utility grid and the technology developments achieved in the electric motors field, the AC railway systems directly fed by power transformers were possible. As a result of this evolution process, there exist five main electrification schemes at the moment: 750V DC, 1500V DC, 3000V DC, 15/11kV 16⅔/25Hz and 25kV 50/60Hz. A good review of their geographical distribution throughout Europe can be found in [3].

The steadily increase in traffic density and velocity in railway lines has evidenced the drawbacks of conventional ERPSS's of dealing with the higher power demanded whilst maintaining good power quality ratios. Furthermore, today's increased interest in reliability and cost effectiveness drive for an active power control capable of managing the power flow between the utility grid, the railway grid and the possible storage systems [4] with respect to economic and technical constraints.

In this situation, electrical railway engineers face the complicated challenge of developing appropriate ERPSS's. The importance of defining a global common direction of evolution is very high because it favors the standardization; the key point to reach economics of scales and improving the interoperability. Fortunately, the outstanding development of power electronics during the last years and the initiated evolution of electrical systems towards smart grids [5], [6] have alleviated this situation showing the way.

All the above reasons motive a comprehensive review comparing currently ERPSS's and their future trends of development. Although there are some other good reviews in literature, they are usually focused on very specific issues, like power quality concerns [7], or do not present intermediate possible configurations [8].

Railway systems are complex systems that involve and interlink many different fields of engineering. Therefore, it is considered necessary to make a short description of their principal elements. An ERPSS is defined as the set of elements necessary to feed the trains ensuring their proper operation [9]. From the electrical power engineering perspective, ERPSS's can be divided into three main systems: the electrical system, the traffic system and the control system. The railway system is the central element of the electrical system and it can be divided into the traction substations, the railway transmission grid when applicable, the generators and storage systems when existing and the catenary. It is important to highlight that the term catenary used in this paper embodies the catenary itself (contact and messenger conductors), the positive and negative feeders where applicable, the rails, and the possible return lines.

The railway system can have two main topologies: centralized and decentralized [10]. As shown in figure 1, in the centralized systems, the catenary is connected by an intermediate railway transmission grid that is fed from dedicated railway power plants and/or the utility grid, whereas in the decentralized systems the catenary is directly connected to the utility grid.

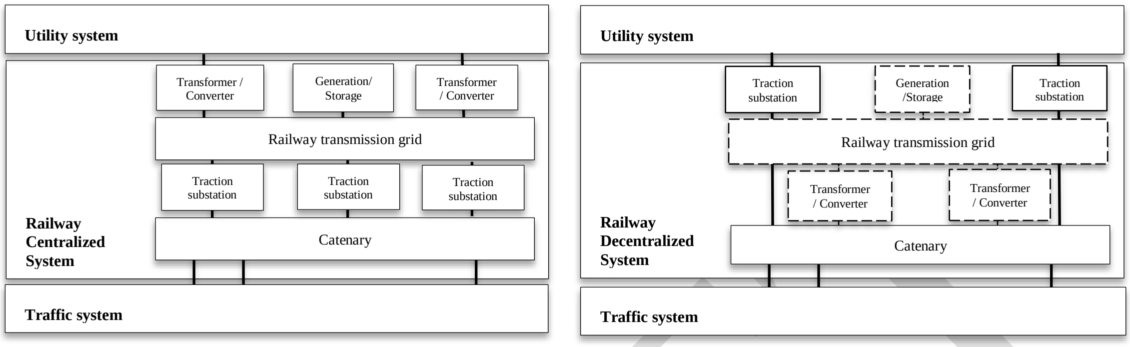

Fig.1 ERPSS's configurations: centralized and decentralized

The centralized systems emerged at the beginning of railway electrification due to the necessity of dedicated reduced frequency generation. However, with the subsequent development of power converters, the decentralized systems have become the dominant topology today with the exception of the countries of Germany, Austria and Switzerland where the centralized topology was strongly deployed at earlier times. It is important to highlight that decentralized systems can also have the possibility of including a railway transmission grid in parallel with the catenary or having generation or storage systems directly or indirectly connected to the catenary [11].

Finally, the traffic and control systems are found. The traffic system is constituted by the trains that consume or inject power depending on their movement, whilst the control system is in charge of guaranteeing a reliable, efficient and economical operation of the electrical and the traffic systems.

The subsequent sections are organized as follows. The second section addresses the transformer-based ERPSS's, from its simplest form to the most recent proposals. The third section is devoted to the conventional and advanced converter-based ERPSS's. The fourth section presents a thorough analysis and a comparison of the previous solutions attending to economic and technical criteria. Finally, in the fifth section, the main conclusions drawn from the paper are described.

2. Transformer-based ERPSS's

As indicated in section 1, the technological development promoted the introduction of transformer-based ERPSS's as a possible solution for railway electrification. Due to their lower investment costs and their simpler operation, they became the most common configuration in new railway lines.

2.1 Conventional configurations

The simplest transformer-based configuration consists of two 25kV single-phase transformers placed at each traction substation connecting the catenary and the utility grid. As shown in figure 2, these two transformers are usually connected to different phases in order to reduce the power imbalance introduced in the grid. This issue requires the installation of a neutral zone that divides the catenary grid into electrical insulated sections. Because this phase shift is accomplished in all substations, this connection also requires a neutral section between different substations. This sectioning represents an obstacle for an efficient use of the energy, since the trains can be only fed by one substation at the same time and reduce the possible use of regenerative braking energy among trains.

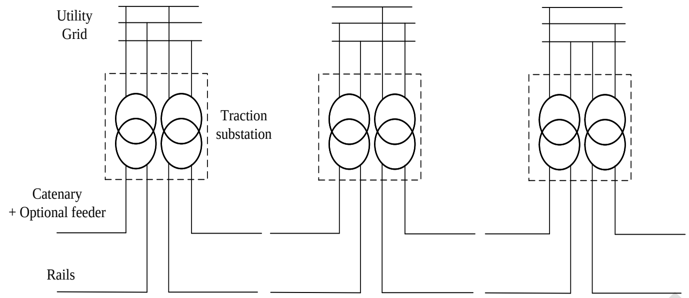

Fig. 2. Mono-voltage ERPSS

The maximum section length is determined by the maximum voltage drop admissible in the catenary. In order to increase this length, new configurations appeared. One of them is the so-called bi-voltage system since it uses two different voltages levels in contrast to the previous monovoltage one.

As shown in figure 3, the bi-voltage configuration uses two single phase 50kV transformers with an earth connected secondary central tap to feed the +25kV catenary and the -25kV feeder lines. To reduce the transmission voltage from 50kV to 25kV, a distance dependent number of autotransformers are placed along the catenary. Due to the use of autotransformers, this configuration is also known as autotransformer (AT) feeding system.

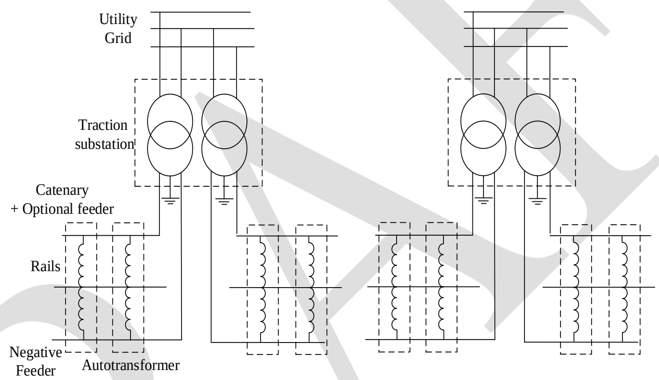

Fig. 3. Bi-voltage ERPSS

It should be noted that generally the negative feeder does not need to have the same voltage as the catenary and/or positive feeders. A more detailed description of these two and other configurations of transformer-based ERRPS's can be found in [12]–[14].

Transformed-based ERPSS's is the dominant technology for new railway lines at present, although they present strong drawbacks from a power quality point of view. The main three issues are: power imbalances, low power factor and harmonic distortion [15].

Phase imbalances are perhaps the main power quality problem for railway engineers. They are produced because traction loads are single phase loads fed from a three phase system. This issue causes a negative sequence current and involves the necessity of finding electrical power supply systems with high enough short-circuit power that can accept such power imbalance [16].

Another significant power quality issue is the harmonics injection. Modern [17], [18] as well as conventional railways locomotives, EMUs (Electrical Multiple Units) and auxiliary services are common important harmonics sources in railway systems that can lead to voltage distortion. As [19] describes, this problem can even be worsened by possible resonances that amplifies the harmonics levels.

Finally, as well as the aforementioned power quality concerns, the influence of electromagnetic emissions constitutes another important factor to consider. In [20], [21], the effect of the railway electrification configuration on the signaling and telecommunication systems is extendedly studied.

2.2 Balanced transformers

Balanced transformers are the main solution for enhancing the power quality concerns of transformer-based RPSS's without using power electronics devices. A simple definition of a balanced transformer is a specially connected power transformer capable of producing an n-phase balanced system from an m-phase balanced system.

In railways systems, the three phase to two phase balanced transformer is the most convenient. There exists a great number of ways of obtaining two phases from three phases, but not all of them are balanced. A balanced connection firstly requires having a balanced set of electromotive forces in both sides and secondly a balanced set of magnetomotive forces on each limb of the transformer. A comprehensive theory about phase transformation can be found in [22].

The four most used schemes are: Scott, Le-Blanc, Impedance matching and Woodbridge connections [23], [24]. However, there exist other interesting proposals in literature [25], [26]. In figure 4, a description of the four previous configuration connections is shown.

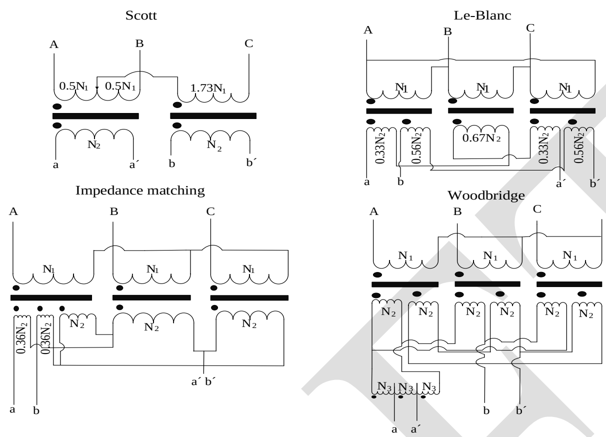

Fig. 4. Balanced transformer connections

It is important to highlight that balanced transformers only produce balanced three phase loads when the two secondary phases are equally loaded. Furthermore, the fact that they usually present complex configurations with unequal number of turns on each limb can lead to a non-perfect balanced situation even when the secondary systems are equally loaded because of the unlikelihood that the internal impedances of each phase were equal.

Many papers have studied the voltage imbalance under various load conditions [27]–[30]. Authors in [31], [32] show a special interest on the load power factor and its definition. However, as described in [33], the use of simple formulas can lead to underestimate its real impact since they neglect the interaction between the railway systems and the electrical system. Regarding harmonics pollution, balanced transformers can represent an interesting option since they can lead to some harmonics cancellation due to their special connections [34].

Another important factor in the selection of a balanced transformer is the material utilization factor. It is noteworthy that the required investment cost for network construction decreases significantly as the utilization factor increases.

Each transformer configuration described has its advantages and disadvantages with regard to the aforementioned factors. In [35] a comparison between them is made according to their technical performance and cost. It concludes that although balanced transformers have a higher cost, they require less power compensating capacity resulting in a lower total investment.

2.3 Converter compensators

Power electronics has brought new possibilities in many fields including electrical transportation systems [36]–[38] and renewable energy grid integration [39]. The use of power electronics converters allows eliminating or, at least, reducing the main power quality concerns found in traditional configurations. There exist a great number of papers presented in the literature that consider power converters in their approaches. The most important are described below.

2.3.1 SVC

The static VAR compensator (SVC) is probably one of the most widely used electronic power devices. Basically, an SVC is a device that provides variable impedance by combining fixed impedances with controllable impedances. Depending on the type of the controllable impedance, they are classified as either TCR if it is a reactor or TCS if it is a capacitor [40].

SVC’s can be installed either in the utility system side or in the railway system side, although for negative sequence current compensation the first option is usually preferred due to its simple control. The control techniques for a load balancing performance are based on Steinmetz circuit. In [41] an SVC with fixed capacitance plus thyristor controlled reactance is applied. Another interesting configuration is found in [42]. It merges the potential of balanced transformer with the SVC functionalities.

Besides performing load balancing, SVC's can also be used for compensating the reactive power and maintaining the voltage in the line [43], [44]. It is important to take into account the possible resonances between the SVC and the system [45].

Compared to other power electronic based systems, SVC based solution has a less satisfactory performance that limits its use significantly. However, it is still a good option when reduced costs and simple controls are needed.

2.3.2 STATCOM

Static synchronous compensators (STATCOM's) can be seen as an evolution of the SVC's that incorporates self-commutated switches. They are well known devices broadly used in the electrical systems. In contrast to SVC's, STATCOM's can simultaneously solve the problems of harmonics, negative sequence current and reactive compensation due the additional grade of freedom introduced by the self-commutated devices [46]. In figure 5, the system configuration is shown.

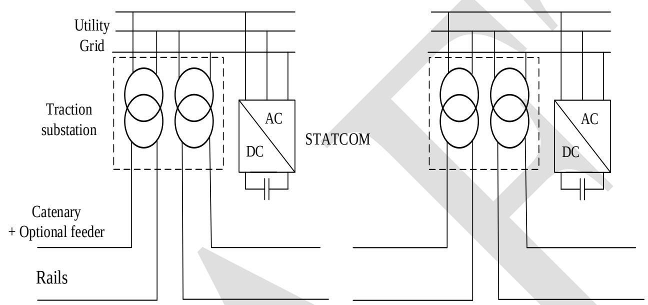

Fig. 5. STATCOM based ERPSS

For the reactive power compensation, the STATCOM can be placed at the end of each electrical section. In [47], [48] this solution is analysed. Like SVC, the main drawback of the STATCOM derives from the bulky capacitors required on the DC bus.

2.3.3 Railway power conditioner

Another railway power supply solution presented in the literature is the so-called railway power conditioner. In its simplest form, it consists of two single phase converters with a common DC link in back-to-back configuration. Each inverter is connected to a different catenary section in the secondary side [49]–[51]. This system configuration is shown in figure 6.

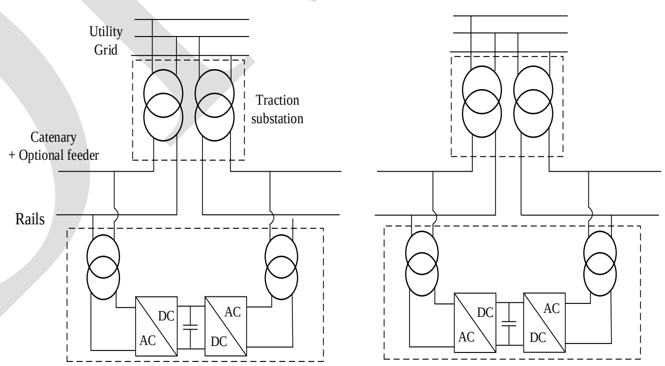

Fig. 6. Railway power conditioner based ERPSS

The converter usually uses full bridge configuration, although there are proposals based on half bridge [52] that allow to halve the number of switches. Both approaches can simultaneously solve the problems of imbalance, harmonics and reactive power.

Another proposal is found in [53], [54] where the two single phase converters are replaced by a three phase converter, reducing the number of connections and associated switches from eight to six. However, this involves connecting two separated sections as it is shown in figure 7. The amount of power compensation capacity required can be reduced using a balanced transformer and a passive filter as it is demonstrated in [55].

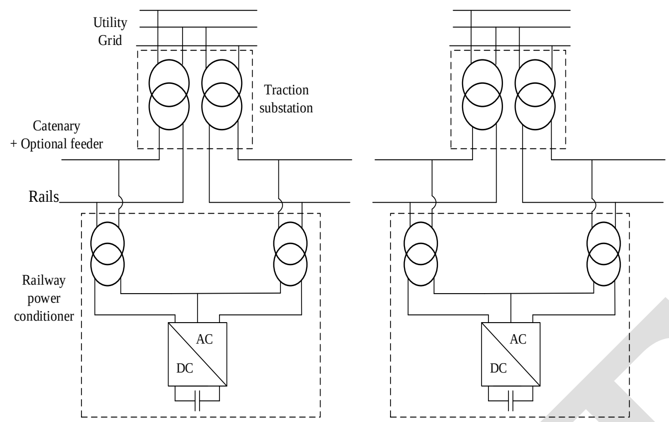

Fig. 7. Three phase railway power conditioner based ERPSS

Many control solutions have been proposed in literature for the railway power conditioner based system [56]–[59]. They are highly effective in solving the power quality concerns, even under distorted grid conditions.

2.3.4 Co-phase

So far, all RPSSs presented make use of two phase feeding connections that implies the necessity of installing neutral zones between these two phases and between phases of the adjoining traction substations. Neutral zones represent a great obstacle for an efficient energy management and a more reliable operation of the high speed ERPSS's [60].

The co-phase railway supply system is a technical solution that can partially solve this problem [61]–[63]. It consists of a three phase to two phase transformer, where one of the secondary phases is directly connected to the catenary while the other is connected to a single phase back-to-back converter. Finally, the converter is connected again to the catenary.

Compared to the previous systems, the co-phase system can reduce by half the number of neutral zones. It also eliminates the negative sequence current and mitigates the harmonics. The transformer used in the co-phase systems can be either a balanced transformer or a non-balanced transformer. In [64] a comparison of the traction transformer type used in co-phase system is made and conclude that the modified Woodbridge is the best option.

The possible modes of operation of a co-phase system can be divided into three different modes: co-phase mode, single phase mode and over-zone mode. The co-phase mode is the normal system operation where the energy is provided by the transformer and converter. The other two operation modes correspond to degraded conditions or in other words, the loss of the traction transformer or the whole substation respectively. In this way, in the single phase mode, only the converter feeds the catenary, while in the over-zone mode power is fed by both adjacent substations.

Some published works that have focused on how to reduce the converter size and its associated cost propose the use of fixed inductors and capacitors [65]–[67]. This approach is known as hybrid co-phase system. Figure 8 shows the configuration of co-phase and a hybrid co-phase system respectively.

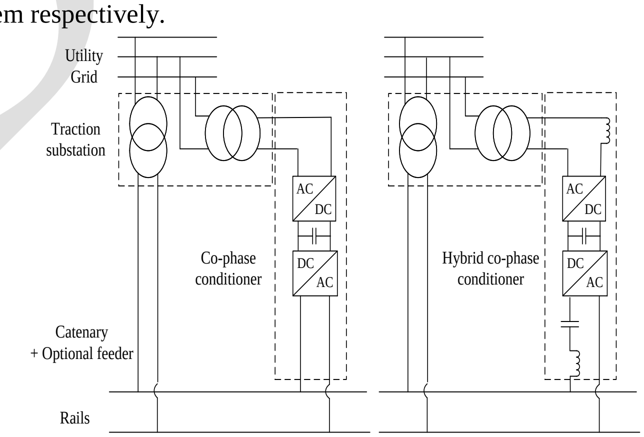

Fig. 8. Co-phase & Hybrid Co-phase based ERPSS

3. Converter-based ERPSS's

Converter-based ERPSS's constitute the second type of railway electrification. So far, their investment costs restricted their use on new power demanding railway lines. However, with the outstanding development in power electronics, this situation has changed significantly becoming not only a possible option, but also advantageous in many cases because of the particular characteristics and additional functionalities they present. Depending on the type of transformation carried out, two main systems can be distinguished: AC systems and DC systems.

3.1 Conventional and advanced AC systems

As it was described in the introduction, the difficulties of AC motors to work with large loads at the industrial frequency led to development of the 15 kV 16⅔ Hz system. Conventional AC converter-based systems connect the utility grid to the catenary by means of rotary or static converters.

Rotary converters were the first to appear and they consist of a motor and a generator connected together with a common axis. Depending on the ratio existing between the number of poles of the motor and the generator, different frequency conversion can be accomplished. A comprehensive description of rotary converters can be found in [68]. The main drawback of these solution is the higher losses, although their overload capacity is still today superior to the static converters one [69].

With the subsequent progress of power electronics, the static converters have been gaining popularity and they are the most widespread at present. There exist two main conceptions for the power conversion: direct or cyclo converters and PWM converters with an intermediate DC link. The latter option is the most used since they present a better stability and allow to reduce the number of power switches used, one of the costly parts. In figure 9, a conventional AC converter-based RPSS is shown.

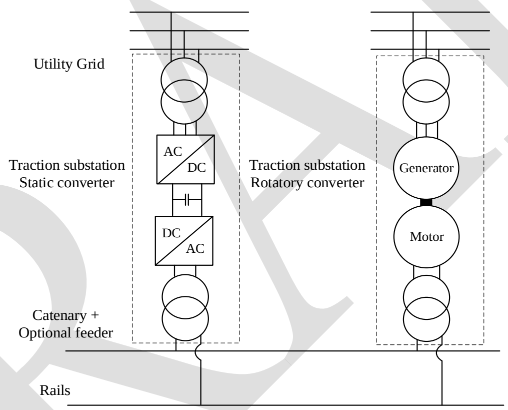

Fig. 9. Traditional AC converter-based ERPSS

The voltage in the catenary can be reached by the series connection of two level converters with high power switches or with multilevel technologies with mature medium power switches [70]. The better signal output obtained in the latter approach allows to reduce the size of filters required converting it into a more attractive option. Among multilevel configurations are: neutral-point clamped [71], floating capacitor [72], cascaded H-bridges [73] and modular [74], [75].

Because of the increase in the voltage capability of power electronic switches, new ERPSS's with higher catenary voltage have been proposed in literature. One of them is the so-called advanced converter-based system [76]–[78], consisting of a three-phase to single-phase converter connected to the 25 kV AC catenary and the utility grid via transformers as it can be seen in figure 10.

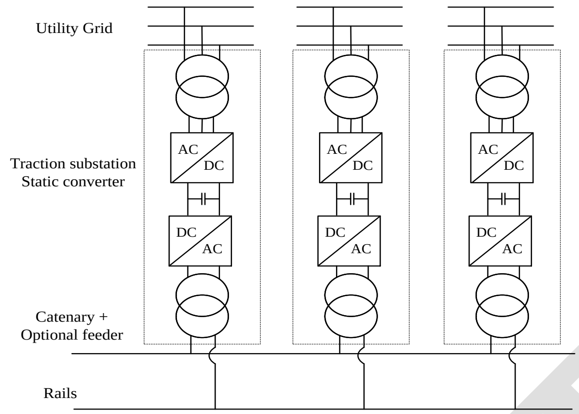

Fig. 10. Advanced AC converter-based ERPSS.

According to [79], the three most costly parts of these converters systems are equally divided into the two transformers and the converter. So that, new technologies without the use of transformers can make this approach more attractive. Furthermore, the use of lower frequencies could also be advantageous because of the lower losses in the catenary, although it is also true that they require heavier transformers on board the train.

Because each single-phase converter controls its output voltage automatically, including frequency, phase and magnitude, all catenary sections can be connected eliminating the necessity for neutral sections increasing significantly the efficiency of the system. Meanwhile, the converters could also compensate the reactive power, harmonics and negative sequence current produced by the railway traffic. At the moment, different people are working on the best way of controlling this type of systems. Due to their similarities with AC microgrids [80], [81], most of the research carried out in this field can be also applied to these system.

As it was mentioned before, although converter-based firstly emerged as a necessity, they can become an opportunity because of the additional functionalities introduced by the new converters. Among all the functionalities provided by these systems, the power controllability is perhaps the most important. It means that each traction substation can adapt its own consumption as long as they maintain the power balancing in the railway grid. The advantages of this improvement in controllability are really important. It can help to enhance the electrical grid reliability avoiding possible line congestions or controlling the power flow considering economic criteria.
Other applications could be providing voltage support to the grid or improving the transient stability of the utility grid by injecting active power. All these advanced functionalities makes possible the transformation of the current passive railway grid into an active smart grid [82].

Although the converters investment seems to be high, the savings in other parts of the electrical infrastructure can also be important. For example, avoiding power imbalances in the grid, combined with the possibility of limiting the maximal load in each point of connection, allow the connection to utility grids with lower short circuit power. However, even in the presence of nearby high short circuit power grids, AC converter-based systems can be competitive due to the reduction in the number of substations required and its more efficient use of the energy because of the non-sectioning catenary.

Finally, it is important to highlight that there exist other less radical approaches to carry out this change of paradigm. For example, [83] proposes to complement the conventional railway transformer-based ERPSS's with additional electronic power converters connected between adjacent electrical sections and allowing to exchange energy between them. The main disadvantage of this proposal is that it keeps unsolved some of the power quality problems found in traditional configurations.

3.2 Conventional and advanced DC Systems

DC converter-based ERPSS's have been traditionally very limited to high power demanding applications. In their conventional configurations they consist of a 6 or 12 pulse bridge rectifier connected to the grid via a standard three phase transformer or a three phase transformer with two secondary windings respectively. Figure 11 shows the conventional configuration of a DC converter-based ERPSS including these two approaches.

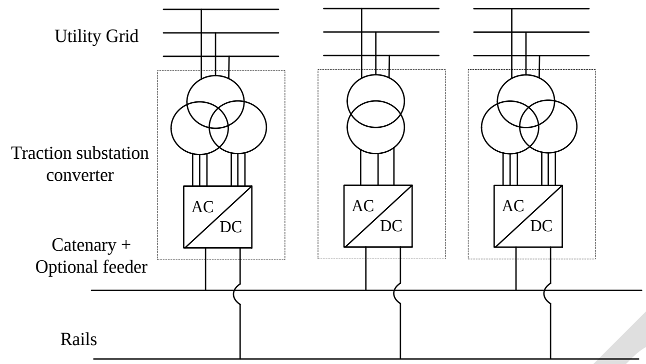

Fig. 11. Conventional DC converter-based ERPSS

The limitation of the use of DC in railway systems is due to the low voltage levels accomplished so far, not because of the DC itself. Increasing the catenary voltage has been always limited by the blocking voltage of the semiconductors. However, the impressive development of electronic switches, like, GTO, IGBT or IGCT has brought new possibilities that allow working at higher voltages without great difficulties as it is shown in table 1.

Table 1:Power switching devices comparison [84]

Technology	GTO	IGCT	IGBT
Self-commutation ability	No	Yes	Yes
Maximum voltage rating	4500V	6500V	6500V
Maximum current rating	4000A	5000A	3600A
Maximum switching frequency	500Hz	600Hz	1000Hz
Switching losses	High	Medium	Low
Conduction losses	Medium	Low	High

The higher power that converters have to transmit in comparison to the converter conditioners previously described, makes the IGCT the best option since its lower conduction losses. On the other hand, the IGBT is the dominant technology for power conditioning.

The idea of increasing the DC voltage is not new [85]. Some studies [86], [87] have addressed the benefits of increasing the voltage in the current railways lines and proposed possible migrations strategies. However, the cost of the system has always made it to be abandoned.

The recent developments achieved in the VSC-HVDC technology have reopened the debate about the suitability of DC electrification for high demanded railway applications. For example [88] proposes to replace the current transformer-based systems used for high speed train lines with modern static converters. This conception is very similar to the advanced AC converter-based systems but allows to reduce the number of converters since it do not require the AC final conversion. Figure 12 shows the configuration of an advanced DC monovoltage converter-based ERPSS.

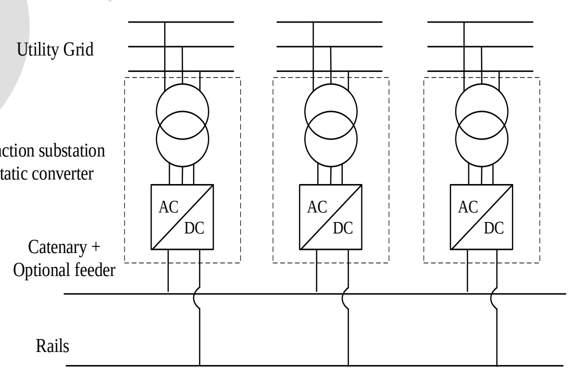

Fig. 12 Advanced DC monovoltage converter-based ERPSS

As in the case of AC systems, DC systems can also present a bi-voltage configuration. In order to achieve it, a variable distance dependent number of DC/DC converters must be placed along the catenary to redistribute the current between the feeder lines and a voltage balancer included in the AC/DC converter to guarantee a balanced DC voltage operation [89]. Figure 13 shows a bi-voltage DC converter-based RPSS.

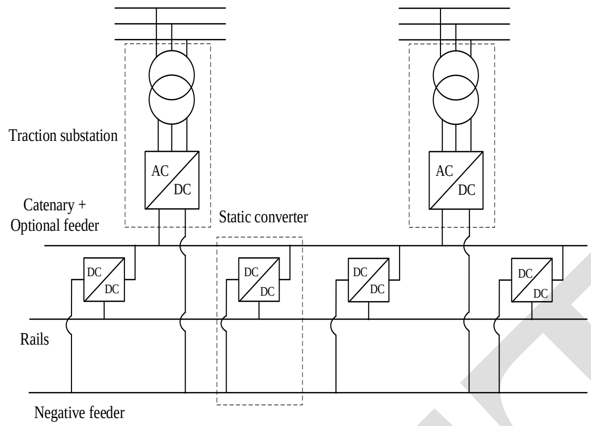

Fig. 13 Advanced DC bi-voltage converter-based ERPSS

The use of direct current in the railway grid allow to decrease significantly the power transmission losses and increasing the distance between traction substations, thus reducing the cost of the system. Besides, the possibility of a bidirectional power flow can make them advantageous even for typical DC railway systems voltages [90].

However, there are also some drawbacks. One of the most important and which is inherent to all DC grids is the clearance of the DC faults. There exist essentially two ways of doing that: using DC breakers or using advanced converting topologies [91], [92]. Although it is a topic under research at present, noticeable improvements are been accomplished. Furthermore, the smaller amount of energy exchanged in the railway systems simplifies the problem dramatically. Another important issue is the need of the development of new rolling stock or converting the existing.

4. Discussion

The right choice of the ERPSS is a decisive factor for the development of more competitive, efficient and reliable railway systems. As discussed before, there exist two main electrification schemes: transformer-based and converter-based. Table 2 provides the main information about all presented ERPSS's divided into three main components: utility system, railway system and traffic system.

Transformer-based systems represent the most widespread option for new railway electrification because of their lower investment costs and simpler operation. However, they present many power quality concerns that can increase their costs significantly. For example, a high power imbalance involves the connection to stronger grids, which often may be located far from the railway lines.

In order to alleviate these drawbacks, two main solutions are found in literature: balanced transformers and power conditioners. Balanced transformers are in general more economical than power conditioners but their performance is less satisfactory. The necessity of having the two sections equally loaded reduces its use to railway lines with high traffic density.

Table 2: ERPSS's comparison

		Voltage, Frequency	Utility system	Railway system	Traffic system
Transformer-based	Conventional	25.000V 50/60Hz	Strong utility grid connections. Medium number of connections.	**Simple traction substation. Simple circuit breakers**. Neutral zones**. Light catenary**.	Heavy rolling stock.
	Balanced Transformers	25.000V 50/60Hz	High-**Medium utility grids connections**. Medium number of connections.	Complex transformer**. Simple circuit breakers.** Neutral zones. **Light catenary**.	Heavy rolling stock.
	Power conditioners	25.000V 50/60Hz	**Possible connection to weaker utility grids**. Medium number of connections.	Converter complexity and reliability. **Simple circuit breakers**. Neutral zones. **Light catenary**.	Heavy rolling stock.
Converter-based	AC Conventional	15.000/11.000V 16⅔/25 Hz	**Possible connection to weaker utility grids.** Medium number of connections.	Converter complexity and reliability. **Simple circuit breakers. No neutral zones. Light catenary.**	Very heavy rolling stock.
	AC Advanced	25.000V 50/60 Hz	**Possible connection to weaker utility grids. Reduced number of connections.**	Converter complexity and reliability. Simple circuit breakers. **No neutral zones. Light catenary.**	Heavy rolling stock.
	DC Conventional	750/1500/3000V 0Hz	**Possible connection to weaker utility grids.** High number of connections.	Converter complexity and reliability Complex circuit breakers. **No neutral zones**. Heavy catenary	**Light rolling stock.**
	DC Advanced	25.000V 0Hz	**Possible connection to weaker utility grids. Very reduced number of connections.**	Converter complexity and reliability. Complex circuit breakers. **No neutral zones**. **Light catenary**.	Need of rolling stock development.

On the other hand, power conditioners present a better performance but their cost are still high with regard to the functionalities provided. There are some interesting proposals in literature like the co-phase system that allows to increase their performance considerably because of the reduction in the number of neutral zones. However, above all these characteristics, it is important to highlight that transformer-based ERPSS's do not allow to control the power flow and so that they do not contribute to the necessary transformation of railway systems into the desired smart railway grid.

In comparison to transformer-based systems, advanced converter–based systems are more efficient because they do not present neutral zones allowing to reduce the voltage drops and the number of substations. Additionally, converters significantly reduce the power quality issues enabling the connection to weaker grids.

Depending on the transformation provided by the converter, AC and DC systems can be distinguished. The lower losses and the easier control make the DC advanced converter-based approach very attractive. However, there are still some doubts about the fault clearance and the necessity of development or adaptation of the rolling stock that makes AC system a more realistic option at present. It is important to highlight that neither AC or DC advanced systems are only proposals and they have been not implemented so far to the best knowledge of the authors.

Regardless the dilemma between AC and DC, and in contrast to transformer-based systems, converter-based systems allow to transform the catenary into a smart railway grid that can adapt the power of each traction substations attending to technical and economic criteria.

The main weak point of these systems is the converter cost. However, taking into account the additional functionalities and the infrastructure savings they provide, this difference is reduced significantly. Besides, the cost of converters has been decreasing year after year because of the wide spread of power converters in many other applications.

5. Conclusions

This paper has classified and described the principal ERPSS's existing at present, their suitability for increasing the transport capacity and the new configurations proposed in literature for their enhancement.

The outstanding development achieved by power electronics has revolutionized railway electrification, bringing converter-based systems to the forefront. The reduction in the number of substations, the possible connection to weaker grids and the capability of controlling the power attending to technical and economic constrains make advanced converter-based systems a good candidate to become the future railway power supply system.

The converter cost is its main drawback, although taking into account the additional functionalities and the infrastructure savings provided, they can be a competitive approach even today.

Last, but no least it is important to highlight that converter-based system do not only constitute a change in the way of trains are fed but also in their operation, that allows to transform them into real smart grids.

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