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Current situation and prospects of electric traction systems used in High-Speed railways

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Abstract

For their operation High-Speed railways use electric power systems with very specific characteristics and different from other electric consumers. The electric traction currently used in High-Speed networks is characterized by being very energy efficient. This is mainly due to the use of AC systems instead of DC systems. On the other hand, the electrical systems used in High-Speed networks are a source of disturbances, both for the railway system itself and for external power supply networks (public grid). The traditional technologies developed in the past continue to be used in the new railway lines, especially in the case of having a sufficiently robust electrical network. On the other hand the expansion of the High-Speed in zones in which this network is not sufficiently powerful, has begun to introduce new solutions based on power electronics equipment. This technology, very implanted in the railway vehicles, has hardly had implantation in the railway infrastructure. The operational advantages of these equipments are several. In addition to the use of lower quality power grids (lower short-circuit power), they also introduce new improvements in traction energy collection. For example, the catenary neutral zones can be removed, the electrical parameters can be regulated and the system performance can be improved in case of operating in a degraded scenario (a problem electrical substation). Although current catenary power systems are quite efficient and operational, integrated operation with these power electronic equipment means that the final conditions improve.

Keywords: Traction Power System, Disturbances, Grid, Unbalanced, Power Electronics, AC feeding systems.

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1. Introduction

The electric traction offers, against diesel traction, advantages such as the possibility of building vehicles of great power and speed, better efficiency from the point of view of energy consumption, and less environmental impact. Undoubtedly this traction is the traction of the present and the future in the railways, occupying the first place in the railway systems of the developed countries with the only important exception of the United States of America. In developing countries this type of traction is also the one that tends to be installed in all of its major railroads.

On the other hand electric traction requires large economic investments in its own facilities (electric power lines, substations and electric power transmission lines for train power), so it requires important economic studies. In any case in railway lines with high traffic speed and high traffic density, the use of electric traction is always necessary.

Traction Power System (TPS) can be distinguished between Direct Current (DC) and Alternating Current (AC) systems with different nominal voltages and power frequencies. Currently the most commonly used TPS is based on 25 kV nominal voltage and 50 Hz power frequency (industrial frequency). Such systems have inherent advantages like simple substation design and low transmission losses compared to DC systems.

1.1 The use of the AC system in High-Speed railways

It can be said that the speed of circulation (v) at which a railway line is designed conditions the electrification system to be used. It is evident that as this speed increases the power demanded by the train is also greater. This is justified considering that in the general formula of drag resistance the term representing the aerodynamic drag is proportional to the square of the velocity:

$$R_a = A + Bv + Cv^2 \tag{1}$$

The term *A* + *Bv* represents the rolling resistance while Cv^2 is the term corresponding to the aerodynamic drag. R_a is expressed in [kN] and *v* in [kph].

On the other hand, in High-Speed railway traction, the fundamental equation of the dynamics applied to a train (with mass *M*) and characterized by an acceleration γ can be written as:

$$F_j - R - M\,0{,}00981\,i = kM\gamma \qquad (2)$$

In this equation *Fj* [kN] represents the total effort on the wheels of the locomotive with all its motors; *Mg* sin *a* represents the gravity component; *i* is the slope expressed in [‰]; *k* represents the coefficient of inertia of the rotating masses. It is dimensionless, slightly higher than 1. The term *kM*, therefore, represents a fictitious mass referenced to the wheels of the locomotive.

In summary a train of mass *M* and drag resistance R_a has an acceleration γ on a line of profile *í*. The motor vehicle must develop in its wheels a total effort *Fj* which is calculated by equation (2) for each speed and slope.

If it is considered that the power P_r in the wheel of the locomotive is expressed by the following equation:

$$P_r = \frac{1}{3{,}6} F_j v \quad (3)$$

This power can be related to the electric power P_{TR} absorbed by the pantograph. To do this, one must know the overall performance of the locomotive which is usually supplied by the manufacturers. In equation (3) the power P_r is expressed in [kW], F_j in [kN] and v in [kph].

As an example if it is considered the case of a Renfe S/100 train (8 cars and a total mass of 393 t), equation (1) is expressed as follows:

$$R_a = 2{,}54 + 0{,}0336v + 0{,}000504v^2 \quad (4)$$

Considering a speed of 300 kph, a drag resistance of 58 kN is obtained. Taking into account that for this train k has a value on the order of 1,04 and considering a non-slope zone and an acceleration of 0,25 ms^{-2}, it obtains a F_j of 158 kN. Using equation (3) P_r acquires a value of 13 MW.

From this example it can be deduced that the power which is necessary to provide from an electric line for feeding a High-Speed train is very high. If it consider a performance near to 1 (losses in the traction link of the locomotive are negligible), it has that the electrical power demanded by the pantograph of the train are also 13 MW. Considering the following equation:

$$S_{TR} = V_{TR} I_{TR}^* = P_{TR} + jQ_{TR} = |V_{TR}||I_{TR}|\cos\theta_{TR} + j|V_{TR}||I_{TR}|\sin\theta_{TR} \quad (5)$$

Taking into account a pure resistive load, the electrical power demanded by the train in the pantograph is:

$$S_{TR} = V_{TR} I_{TR}^* = P_{TR} + jQ_{TR} = |V_{TR}||I_{TR}|\cos 0 + j|V_{TR}||I_{TR}|\sin 0 = |V_{TR}||I_{TR}| \quad (6)$$

It follows that to transport a given power to the train could be acted on the voltage or current so that the required value is obtained. Because it is not in the interest of the intensity value to be high, because the losses that would arise in the transport are proportional to the square of its value, always tends to increase the value of the voltage and to decrease, as much as possible, the of the current. Thus, when working with high values of voltage, it is necessary to always use alternating current.

Considering that, as explained above, the current value is the one that is decreased, a catenary will be required mechanically lighter because the required conductors will be less heavy because they do not need a significant geometric section (a characteristic of this type of catenary is in which only one contact wire is required). The lightness characteristic is essential at High Speed because the contact between the pantograph and the catenary improves.

For all of the above, High-Speed railways should always use AC systems. Unlike the generation of electric power in the power plants, where alternating current is always generated in three phases, the use of alternating current in railways uses only one phase (single-phase alternating current).

1.2 Electric power regenerated

Due to the use of AC systems it can be intuited that the energy efficiency of a high speed line is much greater than in a DC line. This is mainly due to the existence of lower losses in the system.

On the other hand, the management of the electric power regenerated in the braking of the trains has great incidence in the energetic improvement with respect to a line with DC system DC. The braking process a train has to carry out, either to make a stop or to lower the existing slopes along the path, or even to succeed in reaching the speed limits imposed, may lead to important consequences in the final calculation of the energy required by an electric railroad line. Indeed, energy is dissipated in the braking process, some of it is lost in friction brakes (pneumatic brakes), that has no useful use, and some of it is dissipated in the dynamic brakes.

For the dynamic brakes in particular, in the case of having an electric traction train (or a dieselelectric traction one), the braking process involves the generation of electricity. At present, the electricity generated in this type of brake can have multiple destinations:

- Provided the train incorporates regenerative braking, energy is dissipated as heat into electrical resistors provided on board (rheostat brake).
- Provided the train does not incorporate regenerative braking, energy is returned to the catenary. In this case, if there is another train being fed from the same power sector requiring energy, the train may consume the returned energy. This particular example constitutes an optimal process from an energy standpoint. In the case there are no trains demanding energy, two additional cases arise:
    - In case of having a single phase AC power (for high-speed lines), the energy generated is returned to the national grid and can be used by other consumers connected to it.
    - In the case of having DC power, thus existing a rectifier group in the substation, energy is dissipated in the resistors of the rheostat brake provided in the train.

That is, in DC electrifications, energy cannot be returned to the national grid taking into account the current situation, since the substations are equipped with rectifier groups that do not allow current flow into the grid. It also should be noted that the energy is regenerated to the catenary when the train that is stopping has previously fed its auxiliary services (heating, air conditioning).

2. Traction Power System (TPS)

A Traction Power System (TPS) is a system in which it is possible to absorb or generate energy and distribute it to trains in an efficient and safe way. This system represents in itself a power electrical system with its own characteristics. In most cases the TPS is interconnected to the country's general electrical system (Figure 1). It can also constitute its own electrical system. In the first case the AC railway system will operate at industrial frequency while in the second case they will operate at a special frequency (case of some countries in Central Europe).

A common feature is that the electric energy, from its generation to its delivery to the trains, goes through different stages of adaptation and transformation.

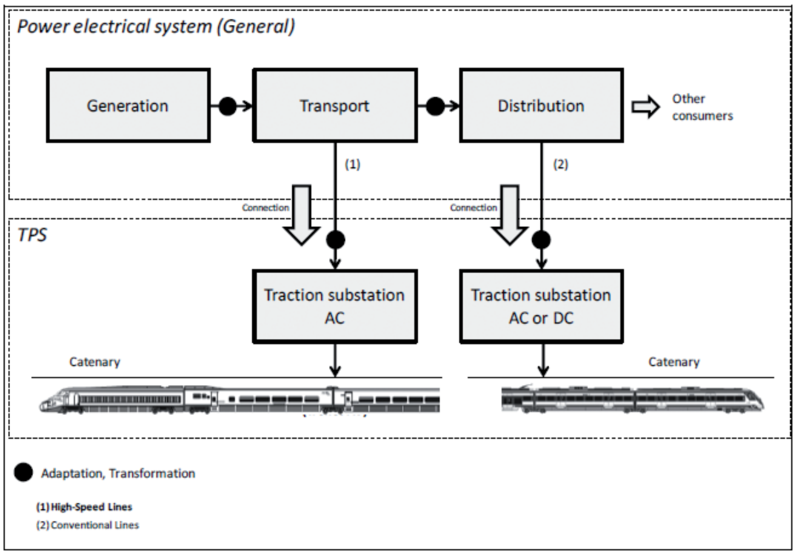

Figure 1. Basic diagram of a power electrical system (general and railway system). Diagram is represented by all the elements necessary for a train with electric traction to operate. In the most common case: 1) Generation sub-system (central of generation); 2) Sub-system Transport (transmission line); 3) Sub-system Distribution (distribution line); 4) High-Speed TPS (traction substation, single-phase electric transmission line to the train (catenary) and train); 5) DC Conventional TPS (traction substation, DC catenary and train). (Source: Author).

The function of the transmission line is to transport large powers from the generation plants to the centers of the load and to the large industrial consumers that exceed the normal limits of the distribution lines. This would be the case of the High-Speed rail, which, due to its power demand, requires a direct connection to the transmission line. This type of line has sufficient short-circuit power to ensure the correct operation of the rail. In this case, therefore, the distribution line is dispensed with and the transmission line is used directly as the distribution line.

3. Source of disturbances

High-Speed trains that operate with industrial frequency (network frequency) are a source of disturbances in the power lines and the own railway environment. It is a load powered by single-phase alternating current, variable in space and time, and power electronics of locomotives. This electronics produces harmonic components of the traction current that flows through the catenary and then returns to the nearby terrain. This fact complicates the operational scenario, taking into account that the rest of the railway systems require electrical cables for their operation.

Although the single-phase alternating current offers an important advantage over the direct current as is its ease of transformation, as a disadvantage is its property of inducing voltages in parallel conductors. Note that in the normal use of alternating current in three-phase systems, the inductions of each phase are compensated by the inductions of the other phases. This fact does not occur in single-phase electrification as there is an electromagnetic disturbance that may be important for other railway installations.

For all of the above it can be said that electrification causes disturbances in the electrical environment of the High-Speed line. These disturbances occur both on the transmission line (as a consequence of being connected to it) and in all the electrical and electronic installations of the railway line.

3.1 Disturbances in the transmission line

These disturbances are mainly the following (Figure 2):

1. Imbalances of currents and voltages at different points in the network, due to the character of the single-phase load.
2. Harmonic currents and voltages that produce the phenomenon of harmonic distortion. They are usually originated by the electronic equipment of the locomotive and even by the electric arcs produced in the interaction between the pantograph and the catenary. Harmonic distortion affects the characteristics of the mains voltage, deteriorating the quality of the service.
3. Voltage fluctuations in the network. It has its origin in the variations of the regime of the load, that is to say, in the randomness of the circulations of the trains and in the variability of the power demanded by each one of them. Voltage fluctuations cause variations in the supply voltage to users near the common connection point.
4. Voltage sag. They are caused by defects in the traction circuit causing harmful effects that may become unacceptable by users connected in the environment of the common connection point.

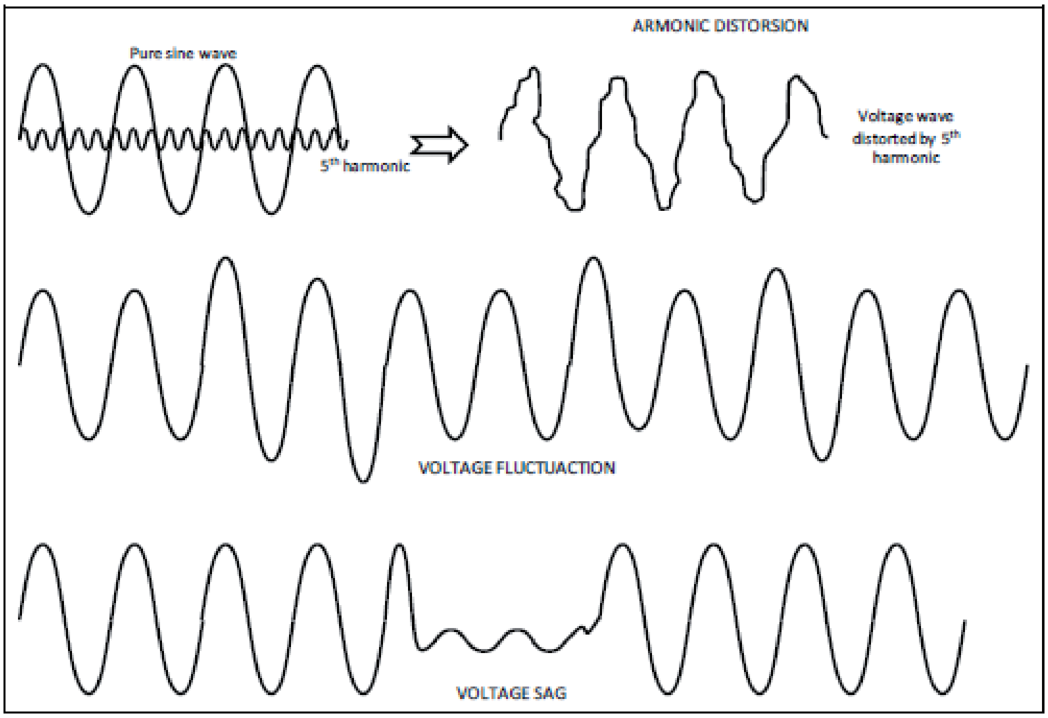

Figure 2. Disturbances. (Source: Author).

3.2 Imbalances of currents and voltages

Of all the disturbances produced on the transmission line, the imbalances of line currents and voltages are the most important (Figure 3). If the same electrical phase of the network were always used, the three-phase system would be decompensated. Therefore, in the electrical supply of High-Speed lines, the phases are always alternated or rotated.

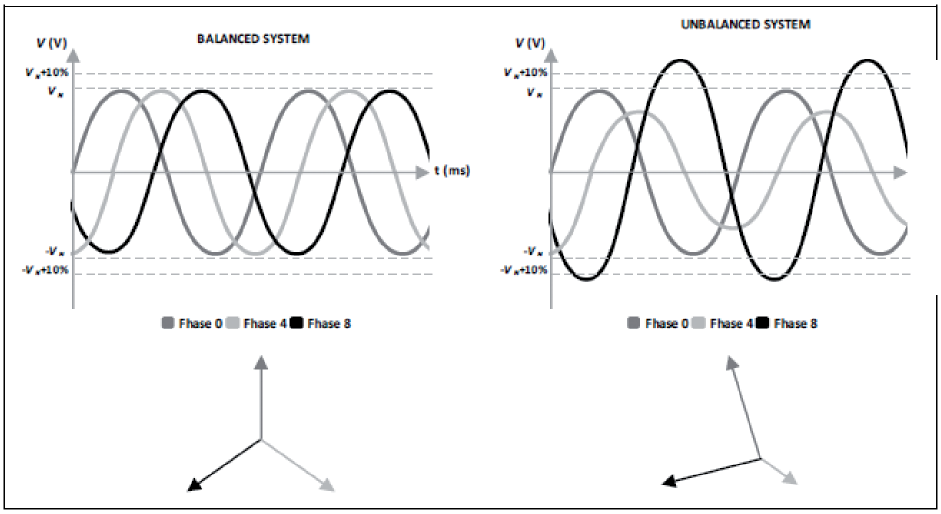

Figure 3. Left) Balanced system; right) Unbalanced system. (Source: Author).

Figure 4 shows a three-phase network to which a single-phase load (represented by a HighSpeed train) is connected. If it considers the unbalanced systems of currents and voltages of a point A in any of the network, both can be represented by two symmetric systems balanced, one direct and one inverse. The ratio of the respective symmetrical components expressing the degree of unbalance. Applying the Fortescue transformation to the calculation of the symmetrical components, it obtains the corresponding values, direct and inverse, of the phaseto-phase voltage at point A. The following equation gives the approximate practical approximate value of the voltage unbalance factor:

$$\tau = \frac{V_{0i}}{V_{0d}} \cong \frac{S_{TR}}{S_{CC}}$$

In this equation τ is the voltage imbalance factor; V_{0i} is the inverse voltage; V_{0d} is the direct voltage; S_{TR} is the single-phase power demanded by the train; and S_{CC} is the short-circuit power of the transmission line.

This relationship between the apparent power of the single-phase load and the apparent short-circuit power at the different points in the network, greatly determines the type of electrical connection to be used between the railway traction substation and the transmission line.

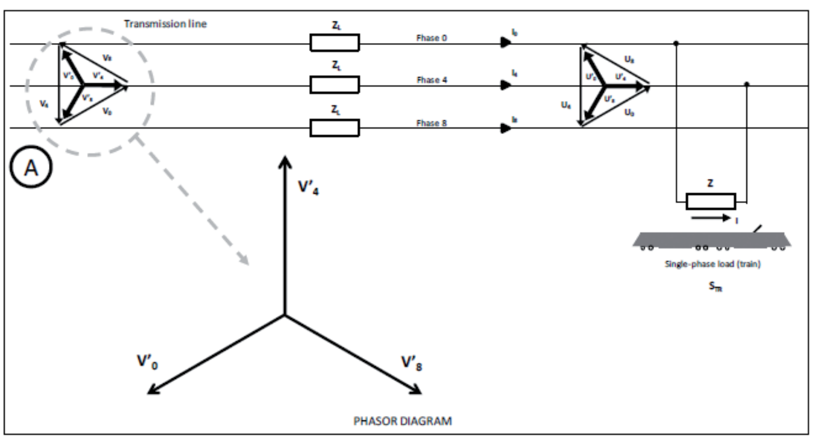

Figure 4. Schematic representation of a single-phase load (train) connected to the three-phase transmission line. Schematic of a balanced three-phase system. (Source: Author).

3.3 Passive techniques to reduce imbalance

Different passive solutions have been introduced for minimizing the effect of voltage unbalance. Although the ideal solution for the railway operation would be to connect the traction substations according to Figure 5A, in practice the substations are connected alternately to the phases of the network as shown in Figures 5B and 5C. Such connections are often referred to as pure single-phase connections. Consequently, the voltages between different feeding sections are 60° or 120° out of phase, so that the network must be sectioned for isolating the paths fed from different substations or different transformers. The phase separation of different feeding sections is done by so called neutral sections.

In the case of Figure 5B it is said that the phase rotation is by electrical substation (the two transformers are connected to the same phase). In the case of Figure 5C the rotation is by transformer.

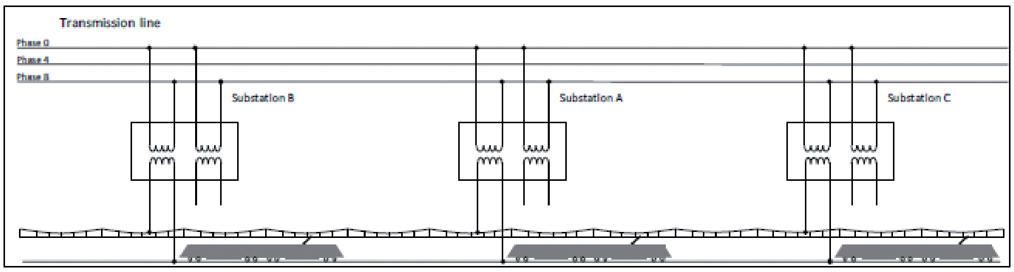

Figure 5A. Pure single-phase connection (ideal but not possible). (Source: Author).

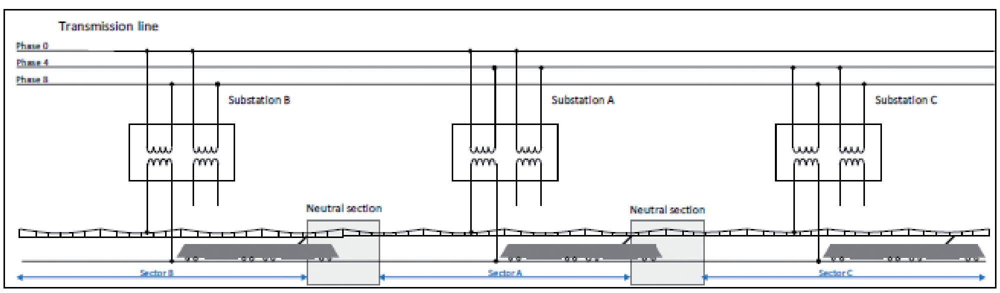

Figure 5B. Pure single-phase connection (phase rotation by electrical substation). (Source: Author).

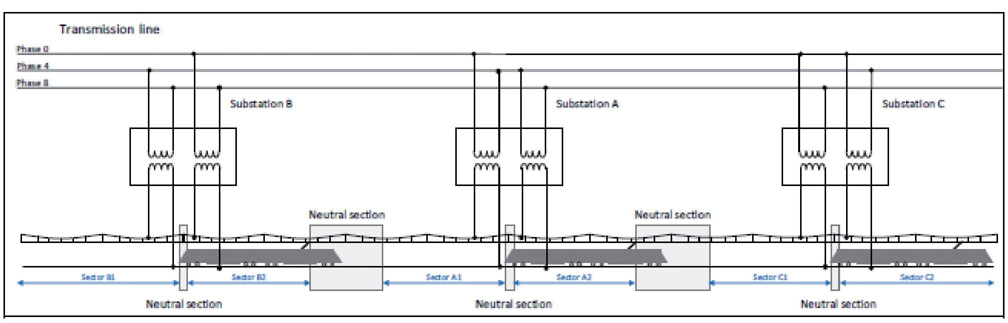

Figure 5C. Pure single-phase connection (phase rotation by transformer). (Source: Author).

3.3.1 Special connections

It is also possible to reduce the voltage unbalance by use of different special types of transformers. The remaining voltage unbalance depends on the type of special transformer used as well as on the distribution of power on the transformer's secondary side terminals.

The connections seen in Figures 5B and 5C are usually those used when there is sufficient short-circuit power in the three-phase substation power supply network. It is observed that the power transformer of the railway substation does not connect to the three phases.

However, if the three-phase supply network does not have sufficient short-circuit power, a single-phase pure connection can not be used. There are other special connections (Scott connection, V-V connection, Le Blanc connection, etc.) that partially solve the presented problem. This would be the case of the Japanese High-Speed network where such connections are often implemented because sometimes the power to High-Speed trains (Shinkansen) is supplied from low-power networks.

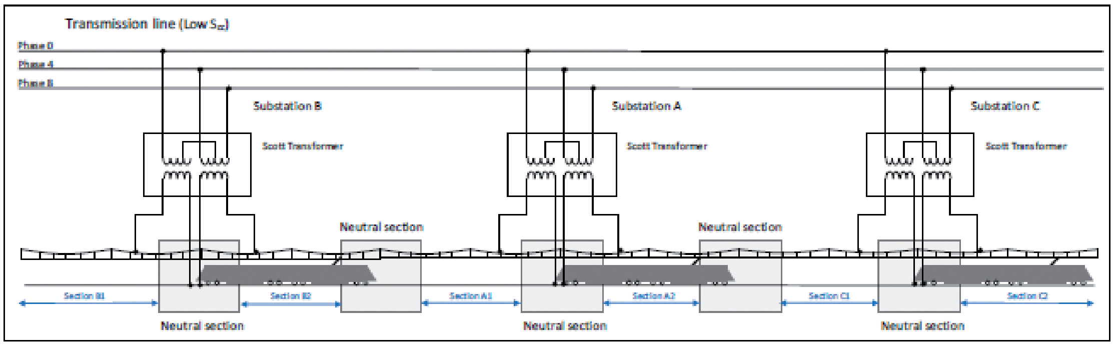

Figure 6. Scott connection (special). (Source: Author).

3.3.2 Neutral section

As seen in Figure 5 neutral sections are installations that are necessary in High-Speed lines as they prevent electrical phase unbalance in the three phase grids that power them. The existence of neutral sections may entail some occasional operating problems and therefore an attempt is made to minimize how many of them there are and improve operation.

Considering the case of the Spanish High-speed network, a neutral section is built with two insulated overlaps between which the no-voltage catenary is installed (Figure 7). According to the indicated diagram, catenary 1 is powered from the electrical phase 2 (voltage V1) while catenary 2 is powered from phase 2 (voltage 2). The de-energised catenary is installed between the two (catenary 3).

The train that is coming along catenary 1 enters into contact with catenary 3 via the first sectioning. Therefore, when the pantograph has lost contact with catenary 1, it only rubs catenary 3 until it reaches the second sectioning, when it starts to come into contact with catenary 3. It should be pointed out that the train enters the neutral section moving by mechanical inertia as its traction switch has been disconnected. It will reconnect when it leaves to be able to be powered from the new stretch again.

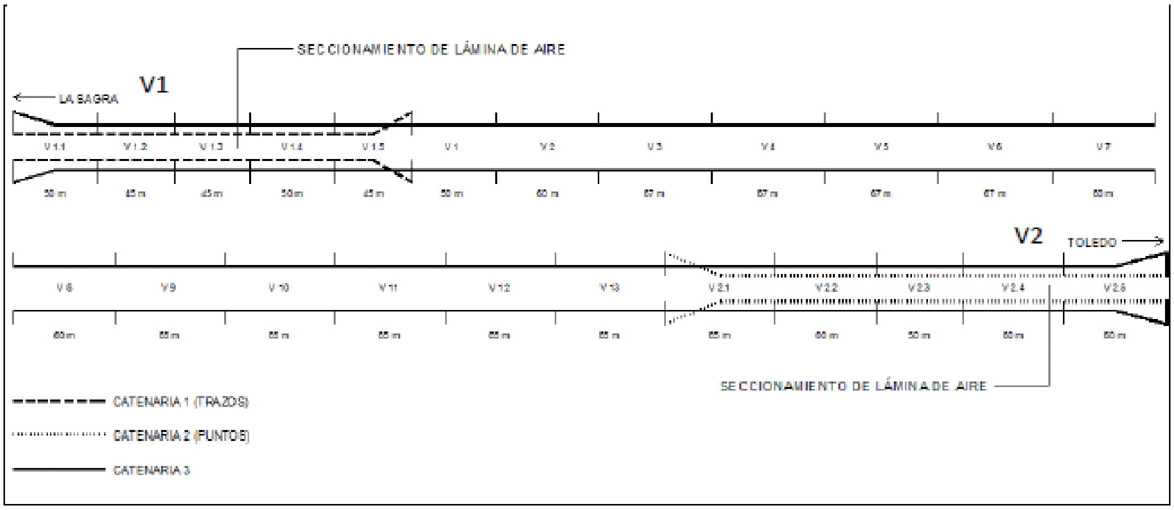

Figure 7. Mechanical layout of a neutral section of catenary. (Source: Adif).

Logically, on passing from catenary 1 to catenary 3, the pantograph will connect to voltage V1. The same will happen with the V2 voltage on passing on the sectioning of catenary 2. The rest of the time, the voltage of catenary 3 will vary depending on the difference of the electrical phases of the voltages of the ends and on the impedance of the de-energised section.

It can be seen that if the time rates of the voltages of the collateral voltage transformers are consecutive (60º phase difference), the electric voltage between the ends of the neutral section is roughly the nominal voltage of the secondary of the transformers. If the rates are not consecutive (phase difference of 120º), the voltage between ends will be roughly √3 times the nominal voltage of the secondary.

A neutral section may be announced with enough time for the train to be able to carry out the opening operation of the traction switch[1]. As seen above, the opening requirement is due to the pantograph energizing the de-energised catenary for a few seconds using the end sectionings, an action that may involve the electrical bypassing of both routes if the train has two pantographs that connect catenaries 1 and 2 via catenary 3 when passing over the sectionings. Furthermore, in short neutral sections, it has been seen that a very high speeds the arc extinction might not have occurred when the pantograph is already in the second sectioning. In any event, the greater the length of the de-energised section, the fewer problems will occur although the loss of speed the train suffers will generally be higher.

The need for installing neutral sections in high-speed lines may entail the following problems:

- Breakdowns on the catenary if a train enters with the traction switch closed. In the event of circulating under ATP this type of incidents will not occur.
- Trains that stop in the section de-energised (for different reasons) and which cannot start up again on their own. Normally a train stopping affects the regularity of the rest of the trains circulating behind it, as some minutes are required for energising the de-energised section and being able to start to run again.
- Generation of fatigue in the train's traction equipment due to continuous openings and closings of the circuit.

It should be pointed out here that the train's lost speed when passing through the neutral

1 Automatic process if circulating under ATP.

section[2] is approximately 9 kph with a total time passed since traction of roughly 22 s and having run roughly 1600 m. Even so, it has been seen that the existence of neutral sections on the line does not affect the total route time and the total amount of electric energy consumed.

Even so, and as to be expected, the ideal situation for operation would be to have as few neutral sections as possible.

3.4 Active techniques to reduce imbalance. Introduction of Power Electronics

Furthermore power electronics applications can be used to actively reduce the voltage unbalance in the public grid. For this purpose different technologies and applications are introduced. Furthermore other advantages can be achieved like reduced voltage drop at the TPS. For example static VAR compensators (SVCs) connected to the three-phase grid in parallel to the TPS reduces the voltage unbalance imbalance but require large harmonic filters due to the switching of the thyristors. Then synchronous static converters (STATCOMs) connected to the three-phase or single-phase traction network were used where they also allow to filter the harmonics produced by the traction loads.

Static frequency converters have also been used to provide the total power required by the substation, although in a smaller number due to the lower cost of the SVC or STATCOM since these are dimensioned for a fraction of the total power of the substation. These frequency converters have evolved from back-to-back converters to the current modular multi-level converters (MMC). There are two configurations for MMC converters: AC/AC direct converters that allow to convert power from a three-phase network from 50 Hz to a single-phase network at 16,7 Hz, and the AC/DC/AC indirect converters that allow obtaining from a 50 Hz threephase network a single-phase 50 Hz network.

Finally, in the last years an electrification system called Cophase Power Supply has been developed (the first 5 MW installation was installed in 2015 on the Shanxi Line in China) which is a hybrid solution between a STATCOM and a converter of the total power of the substation. There are different configurations but in all cases they use a single-phase converter that generates on the three-phase side the current necessary to balance the load and compensate for the imbalance generated by a single-phase or three-phase transformer from which the power is supplied to the single-phase rail network. The converter provides active power to the single-phase network and also allows filtering of the harmonics generated by the loads. As the load to the three-phase grid is balanced, the collateral transformers can be connected to the same phase so it is possible to eliminate the neutral sections.

The inclusion of power electronic converters implies the existence of a system of regulation of control its operation, and to a greater or lesser extent, the behaviour of the rail network: from the SVC that hardly influences the voltage of catenary, STATCOM and Cophase Power Supply that can vary the voltage in catenary, and finally, the total power converter that can modify the voltage and frequency. The last two systems have the possibility of operating without neutral sections which allows them to distribute the load between collateral substations, both at active and reactive power levels. These converters may have implemented control methods to function independently of each other (such as Droop Control which is a method for interconnecting multiple voltage sources for microgrids operating in isolation) or by methods that exchange information, for example, to avoid recirculation by the rail network which is in parallel with the three-phase transport network.

2 Data obtained after the tests carried out by ADIF on HSL 050 (Madrid to Barcelona) and HSL 010 (Madrid to Sevilla). An average speed of 270 kph is considered.

Power Supply	Converter Power Rating (PerUnit Load)	Neutral Sections	Catenary Voltage and Frequency Regulation	Harmonic Compensation	Catenary Short Circuit Protection
Normal	-	Compulsory	No	No	Passive
SVC	0.58	Compulsory	No	No	Passive
STATCOM	0.58	Compulsory	No	Yes	Passive
Full-Power					
Converter	1.0	Can be omitted	Yes	Yes	Active
Cophase Supply	0.5	Can be omitted	No	Yes	Passive

Table 1. A comparison of different feeding systems of AC railways. Source: [1].

4. Another use of Power Electronics: introduction of a static switching system for the operation of neutral sections

Currently some administrators[3] are starting to try static switching systems to allow the training making the transition between electrical phases directly, without being affected in any way and with the aim of improving the operating capacity of the exploitation.

These types of systems use switches on each side of the neutral section, which are represented by semiconductor equipment that allow carrying out a switching in a very short space of time. A very important characteristic of this type of switching is that the exact position of the train should be born in mind.

The operating principle of the system would be as follows (Figure 8):

- The train that is coming along catenary 1 is detected by a detection system that informs the switching system of the next entry of the train into the neutral section.
- At this moment, a close command is established to switch 1 so that the de-energised section is powered at voltage V1. The train does not receive the open command from the traction disconnector at any time.
- Again, the detection system should detect that the train is totally situated inside the deenergised section. When this condition occurs, an open command is issued on switch 1 and a close command on switch 2 so that the de-energised section is powered at voltage V2. This process is short enough for the train not to detect a lack of voltage in the catenary (which would involve opening the disconnector) and there is therefore no loss of traction. The train leaves the neutral section fed by electrical phase 2.
- In a given point of the exit of the neutral section, the detection system identifies the total passing of the train and starts to normalise the neutral section (opening of switch 2), and is ready for the next train to pass.

As indicated above, the switching system should be designed to act in a given time that is determined by the characteristics of the material that circulates on the High-Speed Line. Thus, if a detection system based on electromagnetic pedals is used, the main characteristic that determines the system's reaction time is the distance between the first wheel of the train and the nearest pantograph that it may carry in service.

3 It should be pointed out that the detection system may be represented by a track circuit specially designed for this function (as is the case of the Japanese system), or by a series of electromagnetic pedals that detect the position of the train wheel (system used in test by Adif).

The length of the de-energised catenary is also a fundamental parameter for analysing the viability of installing this type of systems. Specifically it has been able to conclude that if this length is lower than established for an interoperable neutral section (402 m), installing switches will not be viable. The reason lies in considering the circulation in double composition of a 200 m train. In this case if the distance existing between the train's first wheel and the farthest away pantograph from the second composition the train may carry in service (a small auxiliary distance derived from the coupling of the two trains should also be considered), it is concluded that this distance is the one that determines the maximum length of the deenergised section to be used. Therefore, the greater the no-voltage section the simpler it will be to install a system with these characteristics.

5. AC feeding systems

TPS can be considered to be composed of two main subsystems: electric traction substations and the railway distribution line (catenary).

The railway distribution line can also be considered composed of the overhead contact line, the return circuit and other equipment that we could call complementary elements. The overhead contact line is formed by several conductors (mainly contact wire, catenary wire and droppers) and their elements of support, cable and insulation (cantilever, tie bar, steady arm, etc.). Its design is characteristic of each technology company or of each infrastructure manager and is specially designed to guarantee the transmission of a certain maximum current to each train (the maximum recommended current in EN 50388 is 680 A for 25 kV 50 Hz) an adequate electrical contact with the pantograph at a certain maximum speed. The return circuit is composed of the rails and other components that they group in the set of complementary elements. These complementary elements depend on each feeding system used.

The configurations of the TPS networks are considered from the point of view of the existing type of AC power systems and from the point of view of the unilateral or bilateral connection of the substations. The different types of AC systems of feeding to the High-Speed networks are the following:

- Simple feeding with rail return.
- Autotransformer (AT system).
- Coaxial.

The fundamental characteristics that determine the use of each one of them is its capacity to transmit power according to the length of the line and the electromagnetic disturbances that generate to its surroundings.

5.1 Simple feeding with rail return or additional return conductor

This connection is the configuration adopted when there are sufficient connection points to the transport line. In this case the distance between collateral substations is usually between 35 and 40 kilometers. If a nominal voltage value V is considered in the catenary, this connection is often referred to as the $1 \times V$ kV system. Considering the standard value of electrical voltage in catenary (25 kV), it is called 1 × 25 kV system. The operating diagram is shown in Figure 9.

Generally the substation transformers are connected to the same electrical phases. In this way the section of the substation is connected to the same electrical phase, and it is not necessary to install a neutral zone in the substation. The primary winding of each transformer is connected to the grid and converts this voltage to that of the train (25 kV). The secondary winding is therefore connected between the catenary and earth.

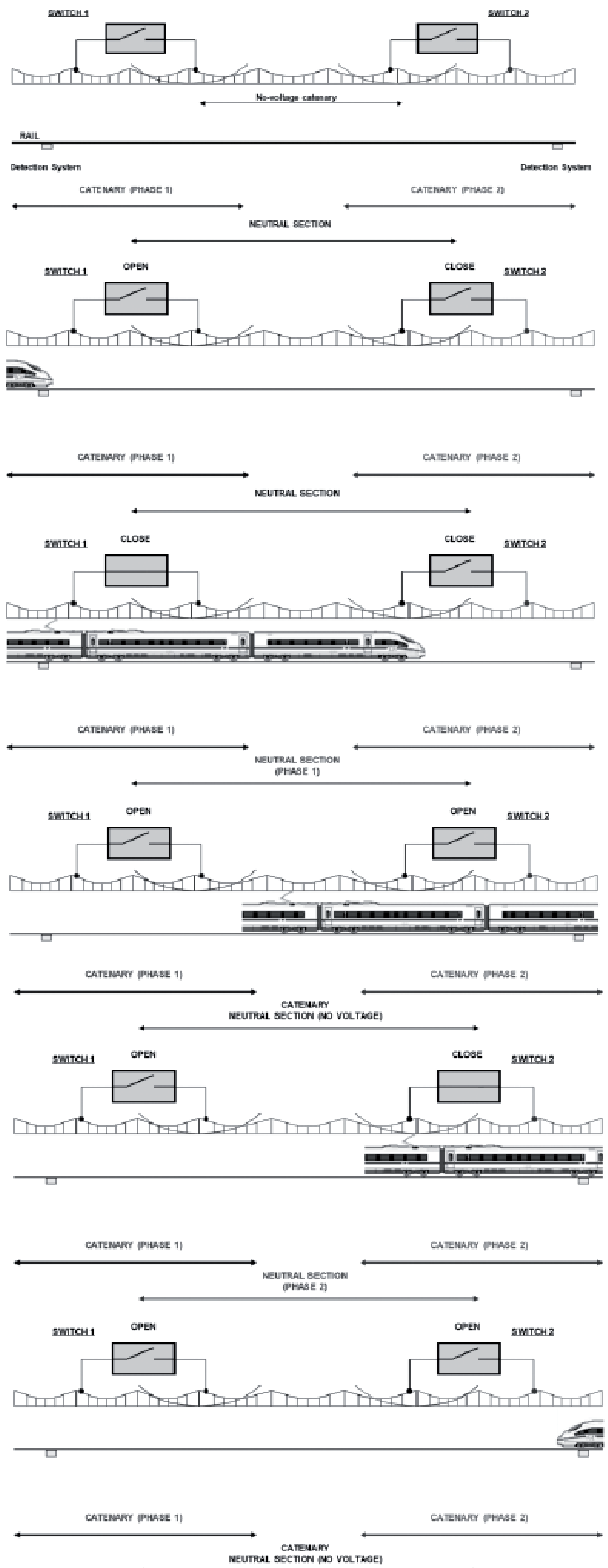

Figure 8. Shunting sequence of the switching system. (Source: Adif).

This connection is economical and easy to exploit and maintain, although there must be sufficient connection points to the grid. As can be seen in Figure 9, energy is transmitted from the substation to the train through the catenary and a reinforcing conductor if it existed. The current return is made by the track rails, the return conductor and the ground.

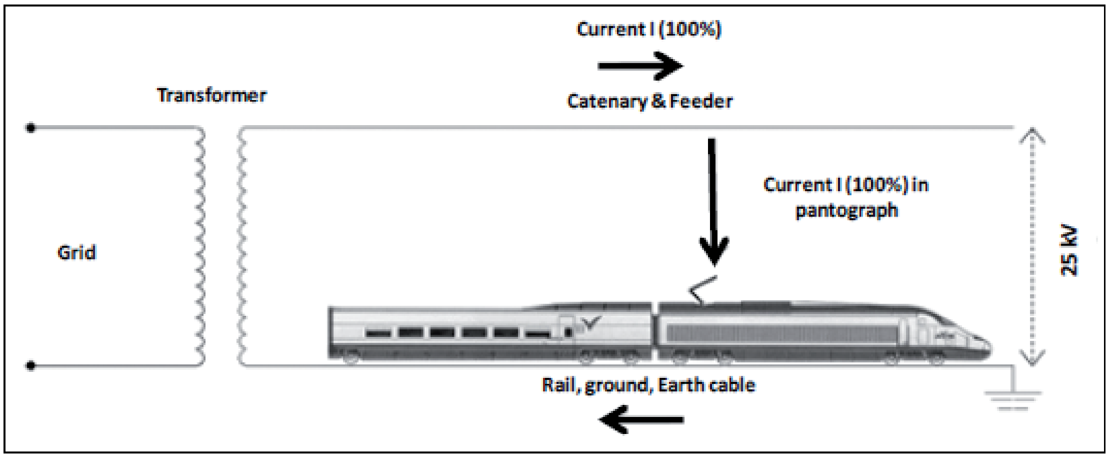

Figure 9. Simple feeding with rail return. (Source: Author).

5.2 Autotransformer (AT)

The AT system is the configuration adopted when there are not enough connection points to the grid. In this case the distance between collateral substations is usually between 60 and 80 kilometers.

If a nominal voltage value V is considered in the catenary, this connection is often referred to as the $2 \times V$ kV system, because as will be seen below, there are actually two electrical circuits in phase opposition. Again, considering the normalized value of electric voltage in catenary, it is called 2 × 25 kV system. This double circuit requires the use of an additional conductor (negative feeder) as well as autotransformers every few kilometers. The main objective is to ensure a voltage drop in adequate catenary considering the greater distance between collateral substations. The operating diagram is shown in Figure 10.

Substation transformers can be connected to the same or different electrical phases. In the latter case each transformer will feed to a semi-section of the substation, being necessary to install a neutral zone in the substation. The primary winding of each transformer is connected to the grid and converts the voltage to twice the train operating voltage (50 kV). The secondary of the transformer has two windings and a central connection connected to ground. A secondary winding is connected between the catenary and earth (25 kV). The other secondary winding is connected between the negative feeder and ground (-25 kV).

Every 10-15 kilometers, autotransformers are connected between the catenary and the negative feeder with its mid point connected to ground. If a train is located at a point in the section, the autotransformers, which have the property of distributing the current that arrives through the central point in two almost equal parts, force the flow of currents indicated in Figure 10. Considering an ideal hypothesis of operation, the distribution of current consumed by the train is made 100% by the catenary to the pantograph. The currents consumed the train are provided depending on the situation of the train. Thus, in the scheme of Figure 10, 50% of the current flows from the substation to the train through the catenary. The remaining 50% is provided by the autotransformers between which the train is located.

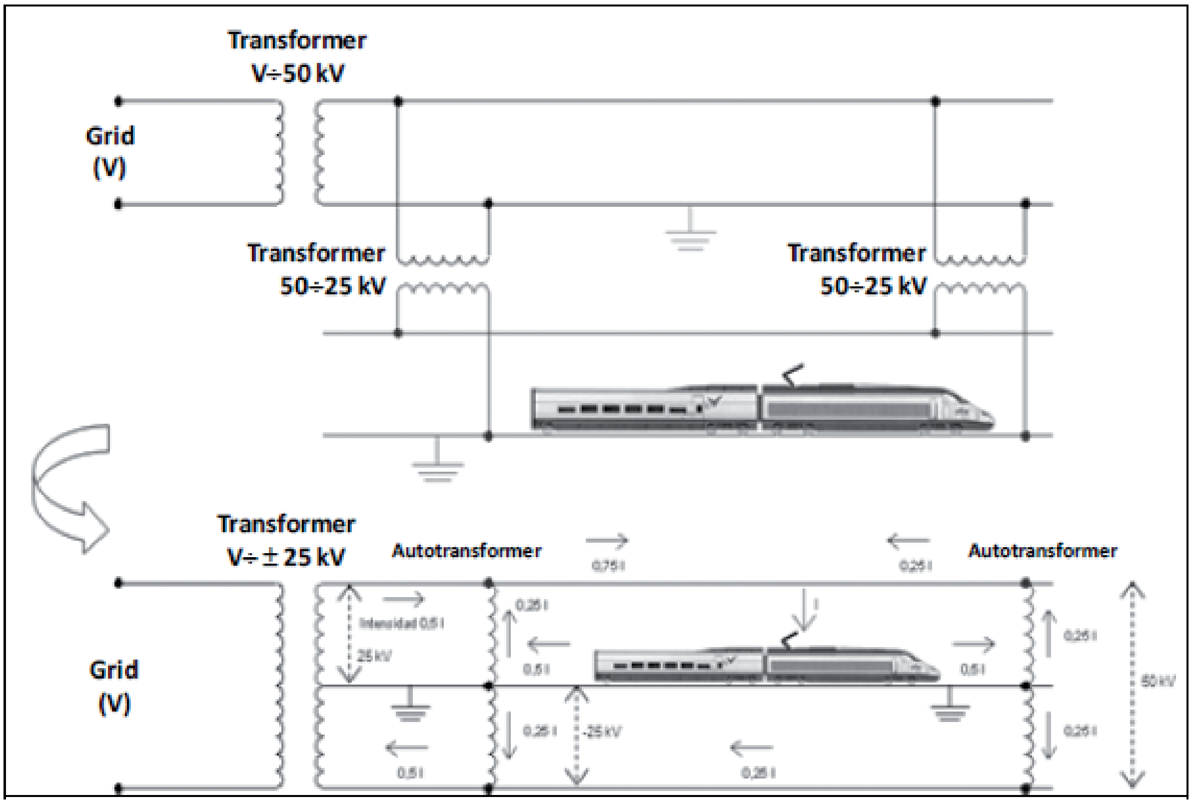

Figure 10. AT system. (Source: Author).

5.3 Coaxial cable

As shown in Figure 11, the coaxial cable feeding system features a coaxial cable laid along the track. Every several kilometers, the inner conductor is connected to the contact wire and the outer conductor is connected to the rail. The cable itself is very expensive but the conductor layout is simple, making it ideal for use where space is limited. Japan is the only country that uses this system (the Tokyo sections of the Tohoku Shinkansen and Tokaido Shinkansen).

In comparison to the overhead line, the coaxial power cable has extremely small loop impedance. Therefore, the load current is boosted in the coaxial power cable from the connection with the catenary. This results in a rail current distribution similar to that of AT system, significantly reducing the inductive interference.

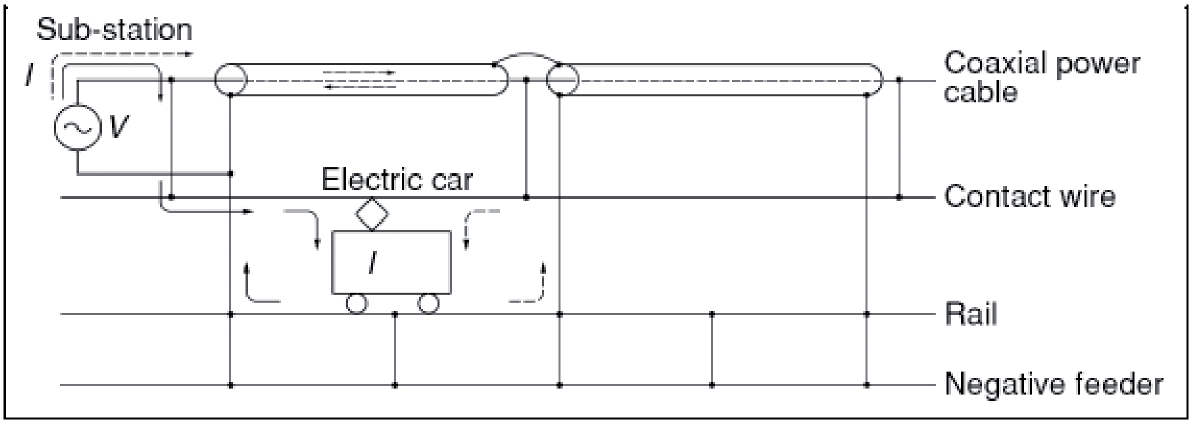

Figure 11. Coaxial cable feeding system. (Source: [2]).

6. TPS of the Madrid-Seville High-speed line: current situation and possible future

At the moment Adif is analyzing the operational advantages that the implantation of new power electronics (Full-Power Converter) in the electric traction substations of the High-Speed line Madrid-Seville would have. It must be considered that these substations have not been modified since the opening of the line (1992) and the current high traffic density recommends analyzing the impact that this new technology could have on the operation of the line.

The main action will be the determination of the design of the converter that allows the flow of energy between the public three-phase network and the single-phase rail network. The objectives are two: to analyze a possible improvement in the affection to the grid; to analyze possible improvements in the power supply to trains, including possible elimination of neutral zones in the catenary.

This High-Speed line has a 1 x 25 kV (simple feeding with rail return system). There are 11 substations with the average distance of 40 km between substations. Each substation has two single-phase 20 MVA transformers connected to the same two phases and three power outputs (one for each direction and another for a section of track in front of the substation itself of approximately 2 km). There are only neutral sections between substations, and there is no neutral section in front of the substation. The tracks are connected in parallel approximately every 10 km by use of disconnectors. The auxiliary systems of the line (technical building, radio stations for mobile communications, tunnel lighting and switch heater) are powered by transformers connected to the catenary.

The substations of this line are connected to the grid with nominal voltages between 132 kV to 220 kV, which have a comparably lower short-circuit power availability than very high voltage networks with up to 220 kV to 400 kV.

To determine the load of the electrification system, simulation software has been used to determine the power demanded or returned by each train at each time point and its position according to the parameters that influence the energy consumption. After determining the power and its position in the track of each train for each instant, and therefore the locations of the loads in the electric circuit, the behavior of the electrification system has been determined. Depending on the time step used in the simulator, the static or dynamic behavior of the system can be analyzed.

Figure 12 gives a schematic supply layout for three substations. The neutral sections at each substation are bridged with bypass switches, the ones between substations are in use.

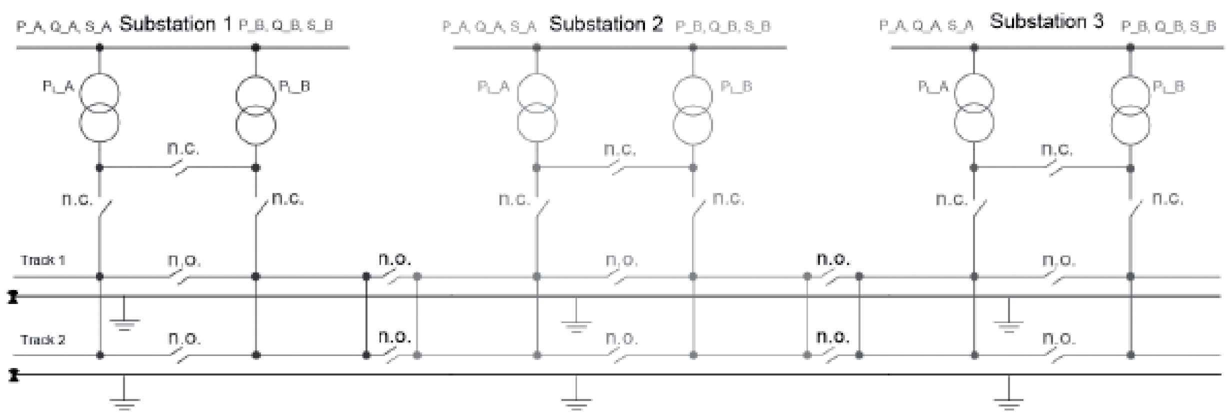

Figure 12. Normal scenario (now). (Source: Adif).

By using converters in each substation, interconnection of all supply sections is possible. Figure 13 gives a schematic supply layout for three substations with converters. All neutral sections at each substation and between all substations are bridged with bypass switches.

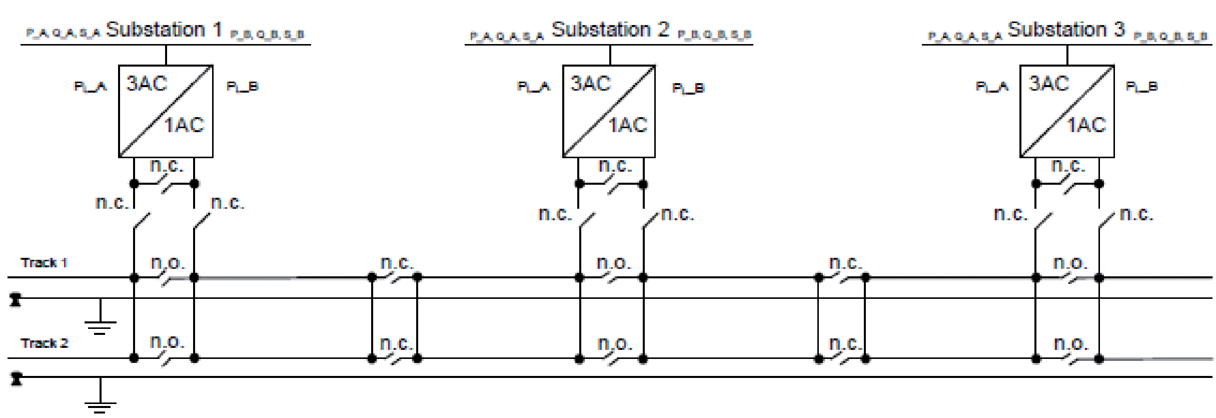

Figure 13. Possible scenario (future). (Source: Adif).

The simulations carried out conclude that the use of this type of converters in a line like the High-Speed line Madrid-Seville has different operative advantages:

- The imbalance factor on the grid is almost completely reduced. This aspect is important because a railway line like this one, with a high traffic density, connected to a transmission line with a not very high short-circuit power, can affect to a greater extent the electric network.
- In case of a degraded scenario (failure of a substation), the voltage drop in the line is optimally regulated (Figure 14).
- Disappearance of the neutral zones, which means that trains do not have to interrupt the traction bus through the route.

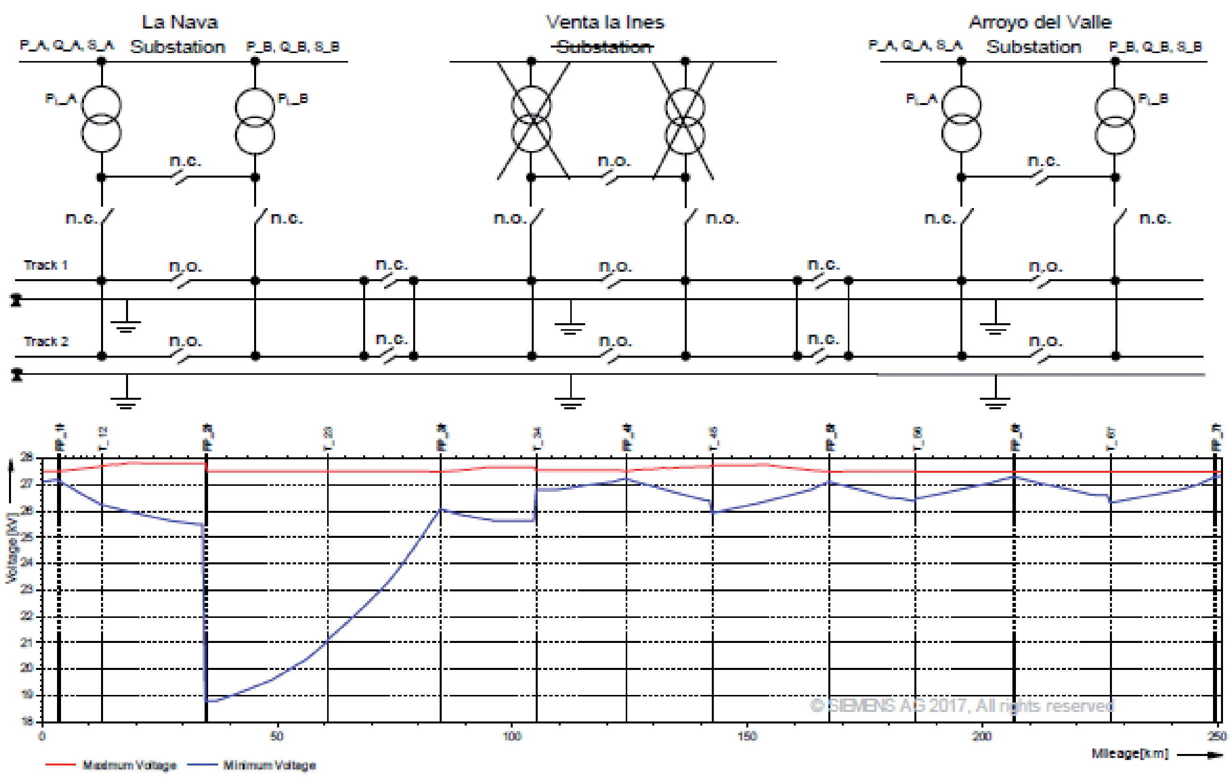

Figure 14A. Degraded operation mode and drop voltage. Conventional system. (Source: Adif).

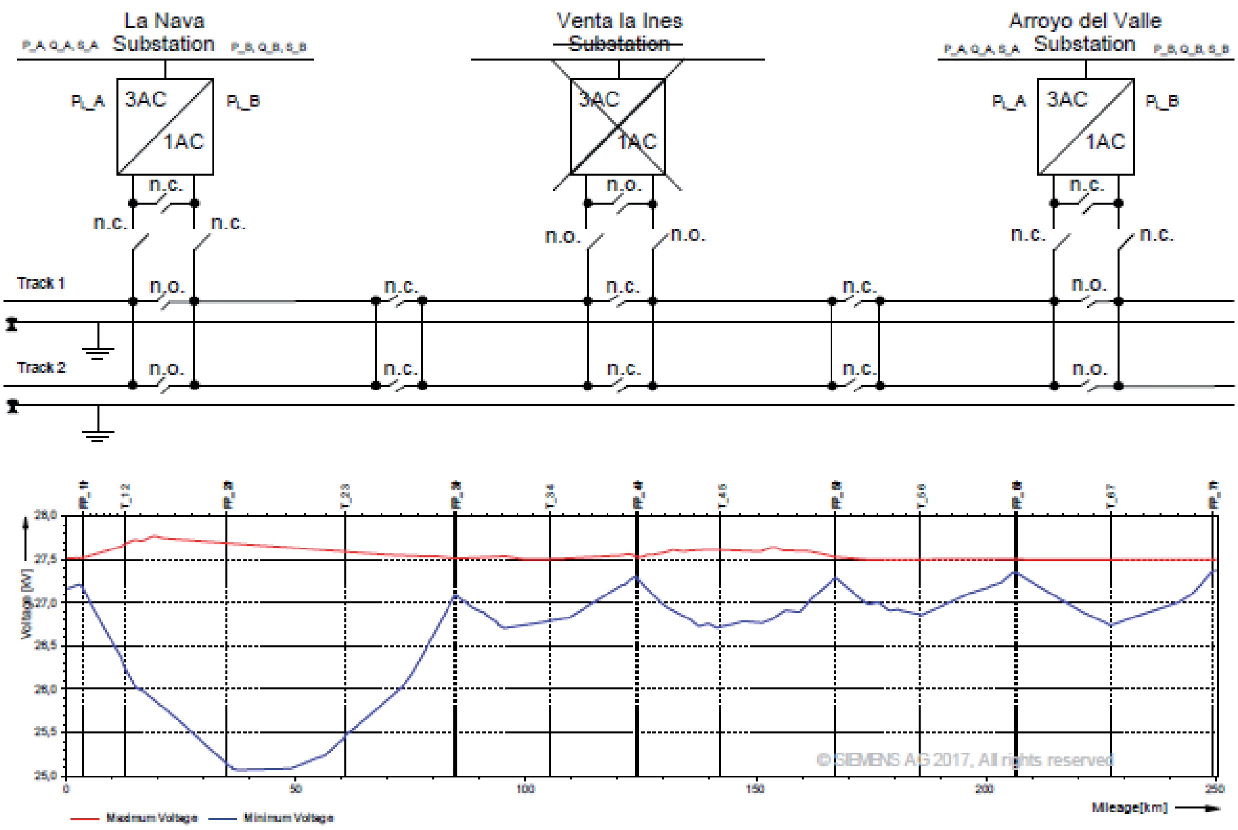

Figure 14B. Degraded operation mode and drop voltage. Converter system. (Source: Adif).

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