PROTECTION FOR DC TRACTION SYSTEMS WITH REGENERATIVE BRAKING

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Master of Science Thesis by:
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Academic year 2016/2017
To my mother,
for her unwavering support,
economical and emotional.
To my family and my friends,
for their presence and encouragement,
along this path.
To professor Morris Brenna,
for his time and dedication.
ABSTRACT

This thesis focuses on the analysis of the interferences that the exploitation of the regenerative braking causes on the protection of the DC traction system; this investigation has been done in order to build a new protection scheme which overcomes all the problems introduced by this technology. The work begins with the description of the regenerative braking, starting from its positive impact on the energy efficiency and arriving to the over-voltages caused on the DC bus voltages. In this thesis a model of a subway system with a rated voltage of $1500\ V_{dc}$ has been realized with Simulink, a Matlab tool; therefore, to well comprehend this model, all the aspects and parts of the traction supply systems are described in the second chapter. Another description part, in chapter 3, concerns the main protections of the DC feeder line, their functions, working principles and coordination. All the block used in the model of the subway line are described in chapter 4. The simulations analysis is performed in the second part of the thesis: the trends of the currents and voltages are analysed in chapter 5, so that the fault conditions which bring down the protections can be carried out. Starting from the results of the simulations, in the last chapter, the new protection scheme is proposed, and it is examined both in the event of ground fault and in that of short-circuit.
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CHAPTER 1

REGENERATIVE BRAKING

1.1 Impact of the regenerative braking on the energy efficiency of the railway

According to the literature, electrical railway systems are one of the main consumers of electrical energy in each country. For this reason, the optimization of these systems is fundamental for both environmental and economic concerns. Nowadays, modern technologies allow the reduction of plant costs, but more important is the reduction of operating cost, that is the energy consumption.

The energy efficiency of railway vehicles is already at a very high level today, in fact, compared with other transportation systems, the specific energy consumption of railways is extremely low. Despite this excellent position, improvements are still possible. In order to continue, in future, the competition with other modes of transportation, the rail transport has to ameliorate. Therefore, in the following the possible improvements concerning energy consumption of rail transport will be shown.

From a mechanical point of view the weight of vehicles and their aerodynamic design are decisive factors for the energy consumption. The reduction of the weight of the structure itself and of the components enables the weight of the train to be reduced significantly, and the consequence of this weight reduction will be a lower specific energy consumption or, alternatively, a possible higher passenger load. As concerns the aerodynamic design of trains, it has been optimized over many years so that the potential for energy saving is almost exhausted. Only few details such as the pantograph or trucks can still be optimized.

Another important problem that can be considered is that of the losses in the power chain. In recent years, the reduction of the losses of converters has been reached by the replacement of the thyristors converters by IGBT converters; but as we can see from the
Figure 1-1 the losses in the traction converters are only a small portion of the losses in the power chain. The major sources of loss are the transformers and the motors.

![Losses Diagram](image)

Figure 1-1: losses diagram

One of the most studied and used way to reduce energy consumption of electric railway systems is to reuse the electrical energy generated during the braking. For high speed trains, the regenerative braking is not economically advantageous, since they brake about once every two hours, instead for subways and urban trams this technology has become fundamental.

Regenerative braking improves the energy efficiency and it extends the life of the braking system too, since the convectional braking wears more slowly. Regenerative braking utilizes the electric motor and, providing negative torque to the driven wheels, it converts the kinetic energy into electrical energy.

In the past, the regenerative energy was conducted to dedicated rheostats and dissipated. This led to a waste of energy and furthermore to an increase of temperature especially in tunnels and locomotives, problem which should be avoid. Nowadays, instead, this regenerative energy is consumed simultaneously by other accelerating trains or stored in storage devices such as batteries, super capacitors and flywheels, for future use. The best solution is to use the regenerative energy immediately, therefore, proper timetables for arrival and departure of trains should be designed so that the simultaneous presence of accelerating and braking trains in one station can be achieved. Clearly, this method has a limit for the stations in which the number of trains is not high. Another problem of this method is represented by the fact that during the day the number of trains in the station is variable; for these reasons, the method of the time-table is not always applicable since it is not always possible used the recover energy instantly.
As the above figure shows, the saved energy with the regenerative braking, in subway transportation system, can reach values up to 45% of the input energy. About 25% of the regenerative energy is used for the start and the acceleration of adjacent train, while, the remaining 20% is stored in dedicated storage systems or dissipated in form of heat by specific resistors.

1.2 Energy Storage Systems

The accumulators are systems that store the energy produced by the regenerative braking in the deceleration phase and then reuse it when necessary, during the next acceleration phase.  

In the last years, in subway transportation systems, these technologies have been introduced in order to reduce the operation costs and to solve partially the tunnel heating problem. An efficient energy storage system not only reduces the energy consumption, but it also stabilizes the line voltage and reduces the peak input power, resulting in lower losses in the electric lines. Usually these energy storage technologies are installed on board the locomotives.

There are three types of accumulation systems, those which use super-capacitors, those which use the flywheels and finally the batteries. As we will see, the flywheels are not used in transportation system both because they do not have the ability to maintain the accumulation over time and because their on-board installation creates the problem of the gyroscopic effect which comes out when we try to rotate the flywheel around a rotation axis different from its own.

In the following super-capacitor and batterie technologies are described.
SUPERCAPACITORS: The metro trains generate high instantaneous currents when they brake. The braking time is around 10–15 s, therefore the recover power is very high, and it is hard to find a convenient energy storage system that can store these high currents in such a brief period of time. Super-capacitors represent the best solution at this problem. Super-capacitors are particular capacitors which are able to store an amount of electrical energy exceptionally large compared to traditional capacitors; in fact, their capacitance value can reach 1000 F.

In supercapacitors, the energy is stored electrostatically on the surface of the material, and does not involve chemical reactions. Given their fundamental mechanism, supercapacitors can be charged quickly, leading to a very high power density, and do not lose their storage capabilities over time: they can last for millions of charge/discharge cycles without losing energy storage capability. Their series resistance is very low; thus, the power losses are limited. Finally, supercapacitors are lighter and less bulky than chemical batteries. On the other hand, the main shortcoming of supercapacitors is their low energy density, meaning that the amount of energy supercapacitors can store per unit weight is very small, particularly when compared to batteries. Other disadvantages of the supercapacitor are its high cost and the high self-discharge.

The construction of supercapacitor is similar to the construction of electrolytic capacitors in that they consist of two foil electrodes, an electrolyte and a foil separator. The separator is sandwiched between the electrodes and the foil is rolled or folded into a shape, usually cylindrical or rectangular. This folded form is placed into a covering, impregnated with electrolyte and hermetically sealed. The electrolyte used in the construction of supercapacitors as well as the electrodes, are different from those used in ordinary electrolytic capacitors.

To store electrical charge, a supercapacitor uses porous materials as separators in order to store ions in those pores at an atomic level. The most commonly used material in modern supercapacitors is activated carbon. The fact that carbon is not a good insulator results in a maximum operating voltage limited to under 3 V. Activated charcoal is not the perfect material for another reason: the charge carriers are comparable in size to the pores in the material and some of them cannot fit into the smaller pores, resulting in a reduced storage capacity.

The energy stored in a supercapacitor is higher than the one stored in a conventional capacitor this is due to the fact that supercapacitors have larger electrodes surfaces (up to 2000 m²/g) higher electrical permittivity and smaller charge separations.

However, compared to a normal battery, they have a lower energy density but a higher power density. Below are reported the equations of a capacitor with flat and parallel plates:

\[ W = \frac{1}{2} CV^2 \]  (1.1)
From these equations, it is evident that an increase in the stored energy can be obtained by acting on the value of the capacity or of the applied voltage.

Capacity increase can be achieved in two ways:
- choosing dielectric materials with a high dielectric constant.
- trying to increase the $S/d$ ratio.

BATTERIES:

In transportation systems when we talk about batteries, we normally mean rechargeable batteries. Rechargeable batteries are batteries whose charge can be completely restored by applying an adequate amount of electricity. Usually the charge is achieved, in a first time, applying a constant current (whose value equals the ratio between the capacity of the battery and its discharge time) up to a certain voltage value after which the charge is completed with a constant voltage and with a maintenance current of the order of some $[mA]$ for each $[Ah]$ of capacity. The capacity of a battery is defined as the amount of energy that a battery can deliver at rated voltage before it is discharged. Capacity is measured in units such as amp-hour $[A \cdot h]$. Batteries also have losses, this is the reason why a conversion efficiency is defined.

The most widespread batteries for historical reasons are lead-acid batteries. They fit well to many applications because they are robust, tolerant to abuse, tried and tested and because of their low cost. However, lead-acid batteries are not advised in transportation systems since they are too big and heavy, and they suffer from a short cycle life and typical not suitable for fast charging.

Lithium-ion and lithium-polymer batteries, on the other hand, have a higher specific energy and a shorter charge time (about ten minutes) so it can be thought a use of these types of batteries in traction systems, especially due to their high power-density. In addition, lithium-ion batteries do not require and maintenance to ensure their performance, have a self-discharge which is much lower than that of other rechargeable cells and they can do more charge/discharge cycles. Anyway, these batteries are expensive because of the employed materials, furthermore the protection circuits, required to manage the temperature and the state of charge (SOC), increase the cost.

The NiCd batteries, now no longer used, must first be completely discharged at 0% and then recharged to avoid the memory effect. They have higher power and energy densities than
lead-acid batteries and a longer useful life too. Any way the high cost and low efficiency does not allow the use of these types of batteries in traction systems. Other types of batteries are in the research phase; therefore, they are not technologically ready to be introduced in the market.

Single batteries are usually assembled into large groups of varying voltages and capacities to obtain the required energy. Battery life should be considered when the investment cost is computed, as the batteries are consumed and need to be replaced. The aging of battery depends on many factors, including stress and high current impulses, which reduce the useful life and performance of the battery itself. Therefore, the battery life is a very important factor; it is necessary to evaluate the number of charge/discharge cycles, in fact, in traction systems are necessary many cycles of this kind, so it is necessary to well consider this parameter in order to avoid additional costs due to excessive substitutions and maintenance.

Let's report in the following a table which highlights all the differences between Lithium-ion batteries and supercapacitors:

<table>
<thead>
<tr>
<th>Function</th>
<th>Supercapacitor</th>
<th>Lithium-ion battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge time</td>
<td>1-10 seconds</td>
<td>10-60 minutes</td>
</tr>
<tr>
<td>Cycle life</td>
<td>1 million or 30,000 hours</td>
<td>500 and higher</td>
</tr>
<tr>
<td>Cell Voltage</td>
<td>2.3 to 2.75 V</td>
<td>3.6 to 3.7 V</td>
</tr>
<tr>
<td>Specific energy (Wh/kg)</td>
<td>5 (typical)</td>
<td>100-200</td>
</tr>
<tr>
<td>Specific power (W/kg)</td>
<td>Up to 10,000</td>
<td>1,000-3,000</td>
</tr>
<tr>
<td>Cost per Wh</td>
<td>$20 (typical)</td>
<td>$0.5-$1.00</td>
</tr>
<tr>
<td>Service life (in vehicles)</td>
<td>10 to 15 years</td>
<td>5 to 10 years</td>
</tr>
<tr>
<td>Charge temperature</td>
<td>-40 to 65°C</td>
<td>0 to 45°C</td>
</tr>
<tr>
<td>Discharge temperature</td>
<td>-40 to 65°C</td>
<td>-20 to 60°C</td>
</tr>
</tbody>
</table>

Finally, we can conclude that:

- Batteries have a higher energy density than supercapacitors.
- Li-ion batteries have the highest energy density per unit of volume, therefore they are more compact and lighter than supercapacitors. Among all the types of batteries, Li-ion batteries represent the best solution for traction systems.
Supercapacitors are better than batteries for their very low charge time. This is a very important parameter, in fact, the storage system must have a fast charge since the power given back by the trains have an impulsive behaviour.

Durability is a significant parameter for the calculation of the investment cost and it depends on the number of charge/discharge cycles that the storage system can stand; as concerns this parameter supercapacitors are far better than batteries.

The cost per unit of power is significantly lower in the supercapacitors.

1.3 Induction motor drives and regenerative braking

Thanks to the modern technological development and to the rapid development of semiconductor technology, which led to the creation of powerful energy converter, nowadays the use of induction motors drives has increased, and this type of motor drive replaced DC motors drives in traction systems.

The AC motors have a high number of advantages:

- AC motors are lighter and more compact than DC motors.
- The absence of brushes and commutator makes the AC motors a cheaper option. In fact, it is well-known that the maintenance of commutators and brushes is very expensive, since the commutator plates wear out quickly due to the friction of brushes on commutator.
- With AC motors, it is possible to obtain a rotational reversing (transition from traction to braking and vice versa) without changing any connections.
- AC motors have a best attitude towards adhesion.

However, also the disadvantages are important and they are:

- When AC motors are operated below its full load capacity, the power factor drops to very low values.
- Poor starting torque. When an induction motor is started, there is no resistance initially, thus, a high starting current (6 to 10 times full load current) flows through the rotor circuit and it may damage the circuit permanently.

The induction machine operates as a motor in traction and as a generator in braking.

The operating condition in traction mode is:

\[ f > \frac{p \cdot n}{2} \]  \hspace{1cm} (1.3)

Thus, it follows that the frequency seen by the rotor is:

\[ f_2 > 0 \]  \hspace{1cm} (1.4)

Since:
\[ f_2 = s \cdot f = \frac{\Delta n}{n_0} \cdot \frac{\Delta n \cdot p}{120} = \frac{\Delta n \cdot p}{120} \]  
(1.5)

It results that the slip is positive; thus, the rotational speed of the stator field is greater than
the rotor speed:

\[ s > 0 \quad (1.6) \]
\[ n_0 > n \quad (1.7) \]

In such conditions both the active and the reactive power are positive:

\[ P_1 = \sqrt{3} \cdot U \cdot I \cdot \cos \phi > 0 \]  
(1.8)
\[ Q_1 = \sqrt{3} \cdot U \cdot I \cdot \sin \phi > 0 \]  
(1.9)

Instead, the operating condition for which the induction machine behaves as generator is:

\[ f < \frac{p \cdot n}{2} \]  
(1.10)

which results from the fact that, in braking mode, the rotor speed is greater than the speed of
stator field \((n_0 < n)\), hence, the slip is negative \((s < 0)\). Therefore, the reactive power is
absorbed (as in the traction mode) but the active power is negative:

\[ P_1 = \sqrt{3} \cdot U \cdot I \cdot \cos \phi < 0 \]  
(1.11)
\[ Q_1 = \sqrt{3} \cdot U \cdot I \cdot \sin \phi > 0 \]  
(1.12)

The torque produced by an induction motor depends on the following three factors:
firstly, the magnitude of rotor current \(I_2\), secondly the flux \(\Phi\) which interact with the rotor
and it is responsible for the induced EMF in rotor \(E_2\), lastly, the power factor \(\cos \phi\).
Combining all these factors together we get the equation of torque as:

\[ T \propto \Phi \cdot I_2 \cdot \cos \phi \]  
(1.13)

The flux \(\Phi\) produced by the stator is proportional to stator induced EMF \(E_1\) \((\Phi \propto E_1)\). Then
we know that the transformation ratio \(K\) is defined as the ratio between the secondary
voltage (rotor voltage) and the primary voltage (stator voltage).

\[ K = \frac{E_2}{E_1} \]  
(1.14)
\[ K = \frac{E_2}{\Phi} \]  
(1.15)

Therefore:

\[ E_2 \propto \Phi \]  
(1.16)

The expression of the rotor current \(I_2\) is:

\[ I_2 = \frac{s \cdot E_2}{\sqrt{R_2^2 + (s \cdot X_2)^2}} \]  
(1.17)

Finally, we know that the power factor is defined as the ratio between the resistance and the
impedance:
\[
\cos \phi = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{R_2^2 + (s X_2)^2}}
\]  
(1.18)

By substituting these values, we obtain:

\[
T \propto E_2 \cdot \frac{s E_2}{\sqrt{R_2^2 + (s X_2)^2}} \cdot \frac{R_2}{\sqrt{R_2^2 + (s X_2)^2}}
\]  
(1.19)

\[
T \propto s \cdot E_2^2 \cdot \frac{R_2}{R_2^2 + (s X_2)^2}
\]  
(1.20)

By removing the proportionality:

\[
T = K \cdot s \cdot E_2^2 \cdot \frac{R_2}{R_2^2 + (s X_2)^2}
\]  
(1.21)

We can now plot the torque as a function of the slip: there are three regions of operation of the induction machine namely motoring \((0 < s < 1)\), generating \((s < 0)\) and braking \((1 < s < 2)\).

![Figure 1-3: torque-speed diagram.](image)

The maximum Torque occurs when the slip is \(S_{\text{max}} = \frac{R_2}{X_2}\) and it results:

\[
T_{\text{max}} = K \cdot \frac{E_2^2}{2X_2} = K \cdot \frac{\Phi^2}{2X_2}
\]  
(1.22)

Therefore, the maximum torque is directly proportional to square of flux, is independent of the rotor resistance and slip.

From the above diagram, it is possible to conclude that the stable region of operation is the one in the interval \(0 < s < S_{\text{max}}\). In fact, in this region the torque developed by the motor is proportional to the slip. Therefore, the motor operation settles at a stable speed for given value of torque. However, if the slip increases beyond \(S_{\text{max}}\) due to high load torque, the torque developed by the motor reduces as the slip increases and this results in stalling of the motor.
In conclusion, the regenerative braking of induction motor takes place if the speed of the rotor is greater than synchronous speed ($s < 0$), but with a reduction of the stator frequency regenerative braking can occur for speeds lower than synchronous speed. Therefore, the induction machine transfers its working point from the I to the IV quadrant and it switches its operation from motor to generator.

Different traction circuits can be used to feed the motors:

![Traction Circuits](image.png)

*Figure 1-4: traction circuits.*

The main difference between the two circuits is that in case b) there is a DC/DC convert whose aim it that of keeping constant the input DC voltage to Inverter. Because of this control on DC voltage, the second system is better than the first. It easy to understand that if we want to use the regenerative braking the inverter should be bidirectional. Two-level or three-level inverter may be used.

### 1.4 Problems of the regenerative braking

Until now, we have analysed the benefits of the regenerative braking. However, when the motor works in the regenerative braking mode, the recover energy will have a significant impact on the DC bus voltage, as consequence, both the bus capacitors and power electronic devices may be seriously damaged by the overvoltage and overcurrent.

To understand the severity of the problem, let’s report the Standard EN 50 163 *Railway applications – Supply voltages of traction systems.*
Table 1-2: European Standard EN 50163.

<table>
<thead>
<tr>
<th>Electrification system</th>
<th>Lowest non-permanent voltage $U_{min2}(V)$</th>
<th>Lowest permanent voltage $U_{min1}(V)$</th>
<th>Nominal Voltage $U_n(V)$</th>
<th>Highest permanent voltage $U_{max1}(V)$</th>
<th>Highest non-permanent voltage $U_{max2}(V)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>D.C. (mean values)</td>
<td>400</td>
<td>600</td>
<td>720</td>
<td>770</td>
<td></td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>750</td>
<td>900</td>
<td>950</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>1500</td>
<td>1800</td>
<td>1950</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>3000</td>
<td>3600</td>
<td>3900</td>
<td></td>
</tr>
<tr>
<td>A.C. (rms values)</td>
<td>11000</td>
<td>12000</td>
<td>15000</td>
<td>17250</td>
<td>18000</td>
</tr>
<tr>
<td></td>
<td>17500</td>
<td>19000</td>
<td>25000</td>
<td>27500</td>
<td>29000</td>
</tr>
</tbody>
</table>

The values considered in this European Standard are the mean value of DC voltage or the rms value of the fundamental AC voltage.

The Standard EN 50163 defines the following quantities:

- **Lowest permanent voltage** $U_{min1}$: minimum voltage value which can be maintained for an indefinitely time.
- **Lowest non-permanent voltage** $U_{min2}$: minimum voltage value which can be maintained for only 2 minutes. $U_{min2}$ is also the lowest operational voltage, which means that under abnormal operating conditions $U_{min2}$ is the lowest limit of the contact line voltage for which the rolling stock is intended to operate.
- **Highest permanent voltage** $U_{max1}$: maximum voltage value which can be maintained for an indefinitely time.
- **Highest non-permanent voltage** $U_{max2}$: maximum voltage value which can be maintained for only 5 minutes.
- **Long term overvoltage**: overvoltage higher than $U_{max2}$ lasting typically more than 20 ms, due to low impedance phenomena e.g. a rise in substation primary voltage. Such over-voltages are independent of line load and may be described by a voltage-time curve only.
- **Medium-term overvoltage**: A transient rise of voltage, lasting typically less than 20 ms, due to current transfer following the opening of switches (e.g. the opening of a circuit breaker).
- **Short-term overvoltage**: an overvoltage lasting less than 20 µs (e.g. lightning strokes)

Nominal voltage in Italian subways is usually 1500 V. Therefore, the allowed values of over-voltages are: 1800 V for over-voltages of indefinite duration and 1950 V for over-
voltages lasting less than 5 minutes. Such values have to be respected for a correct operating of the system, without running the risk of damaging devices and insulations.

1.4.1 Overvoltage due to the failure of regenerative braking

To study the transient process when the failure of regenerative braking happens we use as model the Chinese electrical locomotive SS7. Such locomotive adopts series and separate excited motor. The main circuit is reported in the following figure:

![SS7's main circuit](image)

Where M is the pulling motor, S is the series winding, F is the separate winding and L1 is the smoothing inductance.

When the train runs at regenerative braking, the converter U11 works independently.
The above figure shows the locomotive’s main circuit, using the Γ equivalent circuit to represent the transformer, when T2 and T3 are conducting. Where $L_B$ and $r_B$ are respectively the leakage inductance and resistance of the transformer, while $r_m$ and $L_m$ are the excitation resistance and equivalent inductance.

From Figure 1-5 we can notice that, when T2 and T3 are conducting, transformer current and armature current have the same value and the same direction. Instead, when T1 and T4 are conducting the transformer current is in opposite direction with respect to the armature current.

If we assume that the failure of the regenerative braking is caused by the failure of the commutation in T1 or T4, we can plot the waveforms of rectified voltage ($u_2$), armature current ($i_a$) and transformer current ($i_z$).
As we can notice from the Figure 1-6 the failure in the commutation in T1 or T4 makes the transformer current increase suddenly and this current increase creates an over-voltage in the transformer.

The voltages in primary and secondary side of transformer can be computed and, by neglecting $L_b$, $r_b$ and $r_m$, they result:

$$u_1 = k \cdot u_2$$  \hspace{1cm} (1.22)

$$u_2 = L_m \cdot \frac{di_a}{dt}$$  \hspace{1cm} (1.23)

Where $k$ is the transformer ratio, and $L_m$ can be obtained as:

$$L_m = \frac{d\psi}{di_m}$$  \hspace{1cm} (1.24)

When SS7 work at regenerative braking, the converter U11 works as inverter since the commutation angle becomes $\alpha > 90^\circ$ and the output power is negative.

Let’s show what happens if the failure of regenerative braking occurs at different running speeds. In the following figure voltages and currents waveforms are plotted when the failure happens at $v = 60 \text{ km/h}$ and at $v = 80 \text{ km/h}$.

Figure 1-8: waveforms at different speed.
We can notice that, the higher is the running speed of the train, the higher is the value of the overvoltage, thus the severity of the problems caused to the traction system increases and the breakdown of insulation in transformer and contact line can happen.

In the following table, some values of overvoltage at both sides of transformer are reported at different speeds:

<table>
<thead>
<tr>
<th>( u ) (km/h)</th>
<th>( U_2 ) (V)</th>
<th>( U_1 ) (x10^5 V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>6375</td>
<td>1.29</td>
</tr>
<tr>
<td>50</td>
<td>6786</td>
<td>1.37</td>
</tr>
<tr>
<td>60</td>
<td>7211</td>
<td>1.46</td>
</tr>
<tr>
<td>70</td>
<td>7720</td>
<td>1.56</td>
</tr>
<tr>
<td>80</td>
<td>8323</td>
<td>1.68</td>
</tr>
</tbody>
</table>

### 1.4.2 Overvoltage due to regenerative braking in normal operation

In the previous paragraph, we analysed the overvoltage caused by the failure of the regenerative braking, but regenerative braking causes overvoltage also in normal operation condition.

In the following passages, we will report the overvoltage analysis in a DC catenary fed with a DC rated voltage of 1500 V. According to the European Standard EN 50 163 previously reported, the voltage should be in the range 1000 V ≤ \( U \) ≤ 1800 V in normal operation; instead voltages between 1800 V and 1950 V can only be maintained for few minutes.

Now let us assume that a train is in regenerative braking without another receiver train. From figure 1-9, we can see that, before braking, the network voltage is around 1500 V, which is the rated value. At \( t = 25 \)s the train starts the braking and a transient overvoltage occurs. The peak value achieved is \( U_{\text{peak}} = 2548 \) V, thus the electrical insulation of the train’s equipment and the contact line are damaged. The network voltage peak value can be decreased by setting the operation of the dissipative resistance when the network voltage reaches 1800 V instead of 1950 V, in fact, in this case it results \( U_{\text{peak}} = 2452 \) V, which means a reduction of 3.8% in the overvoltage.
Let us now analyse the situation in which two trains are near a station at the same time; the first train starts braking at $t = \tau$, thus the second train will receive part of the regenerated energy. Figure 1-11 shows the network voltage of the first train (the one which brakes at $t = 25s$) and the figure 1-12 shows the network voltage of the second train.
From these figures, we can notice that maximum voltage peak of the train which brakes is 1810 V which is lower than in the case of regeneration without receiver, where an over-voltage of 2548 V was achieved. Therefore, this confirms the fact that regenerated energy should be used by another accelerating train.

For the second train, which receives the regenerated energy, there is an increase in the voltage at a value of 1900 V. Therefore, in both the conditions the maximum allowable value of 1950 V is not reached.
2.1 Traction Power Substation (TPSS)

The role of an electric traction substation is to transform the energy supplied by the industrial high voltage network, in a useful energy for the traction motors. In DC traction systems, the electric substations are necessary:

1. To perform the AC/DC conversion
2. To transform the network voltage in the contact voltage
3. To protect the traction system against over-voltages and short circuits coming from the industrial grid.

The energy necessary to supply the DC feeder is taken from the three-phase industrial network in high or medium voltage. The MV grid which fed the TPSS has, usually, two values of voltage: 15kV and 23kV with a nominal frequency of 50 Hz.

2.2 Quality of supply voltage

The power taken from the industrial network assume a fundamental role, since it feeds a service of public utility, it must be guaranteed in terms of quality of service. The quality of the supply power can be defined in relation to:

- Continuity of supply: which is characterised by the number and duration of interruptions. Several indicators are used to evaluate the continuity of supply in the distribution networks.
- Voltage quality: which can be measured by parameters such as frequency, voltage magnitude and its variation.
In Europe, the Standard EN 50160 *Voltage Characteristics in Public Distribution Systems* has been generally considered as a reasonable starting point to establish the voltage quality of the supply systems. In this standard, several voltage parameters are defined, and among them the most important ones used to measure the quality of the voltage are:

- **Power frequency variations:** which are defined as the deviation of the power system fundamental frequency from its specified nominal value (e.g. 50 or 60 Hz)
- **Short interruptions:** defined as interruptions of electricity supply for a duration up to 3 minutes. These interruptions are basically accidental, and caused by a transient fault. The 3 minutes’ limit forms the boundary between long interruptions and short interruptions. This means that short interruptions are ranging from few tenths of second up to 3 minutes. The voltage level during a short interruption is considered to be close to zero (usually lower than 1% of the nominal voltage).
- **Voltage dips:** if short interruptions are characterised by a voltage level close to zero (less than 1% of the nominal level), voltage dips occur when voltage levels are still relatively high (typically between 1% and 90% of the nominal level). Voltage dips can be classified depending on their duration and depth.
- **Flickers:** flicker is the visual phenomenon which causes changes in the luminance of lamps and could be annoying to people above a certain threshold. Flicker is caused by rapid voltage changes and is dependent on both the amplitude of the fluctuation and the repetition rates. Flicker is mainly caused by electrical equipment connected to the network by customers.
- **Supply voltage variations:** this phenomenon covers the variation in the voltage level under normal operating conditions. It is an increase or decrease of voltage, due to variation of the total load of the distribution system or a part of it.
- **Voltage harmonics:** these harmonics make a distortion on the ideal waveform of the voltage. The main source of harmonics are the so-called non-linear loads which could be connected to all voltage levels of the supply system. An example of non-linear load in the railway system is the rectifiers used in the TPSS to perform the AC/DC conversion. Due to the increasing non-linear loads, harmonic distortion is increasing in the last few years and is becoming increasingly important.
- **Transient over-voltages:** which are oscillatory or non-oscillatory, highly damped, short over-voltages with a duration of a few milliseconds or less, originating from lightning or some switching operations.
- **Voltage unbalanced:** is a condition where the rms value of the phase voltages or the phase angles between consecutive phases in a three-phase system are not equal.
Table 2-1: supply voltage requirements according to EN 50160.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Supply voltage characteristics according to EN 50160</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power frequency</strong></td>
<td>LV, MV: mean value of fundamental measured over 10 s ±1% (49.5 - 50.5 Hz) for 99.5% of week -6%/+4% (47 - 52 Hz) for 100% of week</td>
</tr>
<tr>
<td><strong>Voltage magnitude variations</strong></td>
<td>LV, MV: ±10% for 95% of week, mean 10 minutes rms values</td>
</tr>
<tr>
<td><strong>Rapid voltage changes</strong></td>
<td>LV: 5% normal 10% infrequently $P_{lt} \leq 1$ for 95% of week MV: 4% normal 6% infrequently $P_{lt} \leq 1$ for 95% of week</td>
</tr>
<tr>
<td><strong>Supply voltage dips</strong></td>
<td>Majority: duration &lt;1s, depth &lt;60%. Locally limited dips caused by load switching on: LV: 10 - 50%, MV: 10 - 15%</td>
</tr>
<tr>
<td><strong>Short interruptions of supply voltage</strong></td>
<td>LV, MV: (up to 3 minutes) few tens - few hundreds/year Duration 70% of them &lt; 1 s</td>
</tr>
<tr>
<td><strong>Long interruptions of supply voltage</strong></td>
<td>LV, MV: (longer than 3 minutes) &lt;10-15/year</td>
</tr>
<tr>
<td><strong>Temporary, power frequency over-voltages</strong></td>
<td>LV: &lt;1.5 kV rms MV: $1.7 U_c$ (solid or impedance earth) $2.0 U_c$ (unearthed or resonant earth)</td>
</tr>
<tr>
<td><strong>Transient over-voltages</strong></td>
<td>LV: generally &lt; 6kV, occasionally higher; rise time: ms - μs. MV: not defined</td>
</tr>
<tr>
<td><strong>Supply voltage unbalance</strong></td>
<td>LV, MV: up to 2% for 95% of week, mean 10 minutes rms values, up to 3% in some locations</td>
</tr>
<tr>
<td><strong>Harmonic voltage</strong></td>
<td>LV, MV: view Table 2-2</td>
</tr>
<tr>
<td><strong>Interharmonic voltage</strong></td>
<td>LV, MV: under consideration</td>
</tr>
</tbody>
</table>
Table 2-2: values of individual harmonic voltages for orders up to 25, according to EN 50 160, given in percent of the nominal voltage.

<table>
<thead>
<tr>
<th>Order h</th>
<th>Relative voltage (%)</th>
<th>Order h</th>
<th>Relative voltage (%)</th>
<th>Order h</th>
<th>Relative voltage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>6</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>9</td>
<td>1.5</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>3.5</td>
<td>15</td>
<td>0.5</td>
<td>6...24</td>
<td>0.5</td>
</tr>
<tr>
<td>13</td>
<td>3</td>
<td>21</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.3 Structure of the TPSS

TPSS have been built during years together with the construction of new lines or with the extension of existing ones. For this reason, TPSS have many different technologies. However, in a generic TPSS we can distinguish three parts:

- High Voltage AC side
- Conversion groups
- DC side

In the following paragraphs, these three parts and all their components are described.
2.3.1 High voltage AC side

The AC section is the first section we meet coming down from the industrial high voltage network. In this section, we can find:

I. Three phase primary lines which connect the TPSS to the industrial grid;
II. A ground disconnector which is usually open, but it can be closed in case of maintenance or fault;
III. A first group of switching devices which are used to protect the high voltage network;
IV. Three phase bus bar system;
V. A second group of switching devices which are used to protect the conversion group;

With the term primary lines, we mean electrical lines with rated voltages higher than 1 kV, fed with an AC current at 50 Hz or 60 Hz. The three phase primary lines are connected to the high voltage industrial grid and their purpose is to provide energy to the TPSS at high voltages, in general 200, 132, 66 kV.
Three-pole disconnectors are electromechanical devices used to ensure that an electrical circuit is completely de-energized for service or maintenance. Standards state that, in case of maintenance or works which required nil voltage, the separation of the line must be visible. Therefore, the disconnectors give a visual indication of the disconnection of the line and they do not take command from automatic devices to avoid prompt reclosing.

The main difference between disconnectors and circuit breakers is that disconnectors are off-load devices, intended to be opened only after the interruption of current by some other control devices. In fact, disconnectors don’t have a mechanism for the suppression of electric arcs, which occurs when conductors, carrying high currents, are electrically interrupted.

The HV disconnectors are usually structured in three columns for each phase. Supporting insulators at both ends are fixed while the middle one (called driver insulator) can be rotated on its vertical axes and it supports and operates the arm.
Figure 2-3 shows the operating principle of the disconnector. From the open position, the arm rotates to enter directly the fixed contacts at the ends of the disconnector. The disconnector can be supplied by manual or motor operated mechanism.
The disconnectors placed near the HV primary lines have in addition an earthing switch unit, which connect the three phases of the primary line to earth in case of maintenance.

The aim of the circuit breakers is to interrupt or give continuity to the circuit in which they are inserted. It must ensure an uninterrupted flow of currents in the network under normal operating condition, and it has to interrupt the flow of overcurrents in a faulty network, so that such overcurrents cannot cause damages to the circuit. It may also be required to interrupt load current under some particular circumstances (e.g. in case of maintenance).
Unlike the disconnectors, the circuit breakers can be opened and closed under load. Instead they differ from fuses because they “trips” to open the circuit and they can be reset, while the fuses melt and hence must be replaced. When the contacts of the circuit breaker separate, an electric arc occurs between them. Since this arc is dangerous, the circuit breaker should be capable of quenching the arc as soon as possible before the arc causes damages to the equipment and to the personnel. For circuit breaker used in AC system the extinction of the arc represents a less severe problem than in the DC circuit breaker. In fact, in an AC system, current naturally drops to zero after every half-cycle and hence, at every current zero, the arc extinguishes for a brief moment. The most employed high voltage circuit breaker use SF6 gas as insulation and quenching medium.
For three-phase system three-pole circuit breakers are used. In fact, they have three poles in series with the three live conductors of the electric circuit being protected, and each pole contains an insulation fluid which is able of eliminating the electric arc generated in the instant in which the circuit breaker opens.

In figure 2-4 we can notice some components such as Surge Protection Device, measuring transformers and auxiliary services transformers which are not represented in figure 2-1. Current transformers and potential transformers are used for either measuring purpose or for giving the input to the relays.
The purpose of the SPDs is to protect the devices of the AC side from over-voltages conducted by the primary lines. In the most recent TPSS, a SPD is installed just before the power transformer in order to protect it since the power transformer is the most expensive and sensible device of the AC side.
Surge arresters are constructed with materials that exhibit a strong non-linear voltage-current relationship. This means that the resistance of the arrester should be dependent on the voltage applied across the block. An ideal arrester should have infinite resistance when the voltage across it is normal and zero resistance when the voltage exceeds the turn on voltage. Different types of SPD can be used in ESS, but the most used is zinc-oxide surge arrester.

The auxiliary services transformer is needed to supply all the secondary circuits of the ESS. It is supplied from one of the two secondary windings of the power transformer. It has a natural cooling and it is insulated with oil-impregnated paper. Usually, the nominal voltage of the auxiliary services is about 380÷400 V and the sizing powers are variable, normally, comprised between 50÷160 kVA.

### 2.3.2 Conversion of energy

In this part of the TPSS, transformers allow the potential lowering and rectifiers ensure the conversion of the alternative current into direct current. The direct current consequently generated by the rectifier is distributed in the DC side and then flows in the train thanks to the pantograph. The unit group transformer–rectifier is commonly called conversion group. Usually the TPSS are equipped with two or three conversion groups (only rarely with one) that provide a total power which goes from 3600 kW to 5400 kW.
GROUP TRANSFORMER

In TPSS can be found two types of transformer: oil-type transformer and dry-type transformer. The presence of a constructive typology rather than the other mainly depends on the period in which the TPSS was built. Below, we highlight the advantages and disadvantages of these two types of transformer.

OIL IMMERSED TRANSFORMER: The core and coils of oil filled transformer are, as the name implies, immersed in the oil contained in a metallic tank. The oil has two purposes. First, it is the fundamental element of the insulating system. Second, the oil transfers the heat, produced in copper by the Joule's effect and in iron by hysteresis and eddy currents, away from the windings to be dissipated by the cooling fins, tank surface, or radiator. These types of transformer are usually equipped with a conservator tank, which is a cylindrical tank mounted on supporting structure on the roof of the transformer main tank, and it has a volume of about a tenth of that of the main tank. The main function of the conservator tank is to provide an adequate space for the expansion of the oil inside the transformer when the temperature rises. It also acts as a reservoir for transformer insulating oil. When the transformer is loaded, the temperature of the transformer insulating oil increases, consequently the volume of the oil increases. As the volume of the oil increases, the air above the oil level in conservator will come out. Again, at low oil temperature, the volume of the oil decreases, which causes the volume of the oil to be decreased which again causes air to enter into conservator tank.

The natural air always consists of more or less moisture in it and this moisture can be mixed up with oil if it is allowed to enter into the transformer and it can shatter the dielectric strength of the oil. To solve this problem the best solution consists in connecting with the conservator tank by means of a breathing pipe, a silica gel breather, so that the air is filtered from the moisture. Since this filter is quite delicate, it is necessary to replace it periodically. In the above figure an oil immersed transformer used in an old TPSS is showed.
DRY TYPE TRANSFORMER: air is used as the cooling medium instead of oil. The dry type transformer is of two types. They are:

- **Cast Resin Dry Type Transformer (CRT):** is used in the high moisture areas since its primary and secondary windings are encapsulated with resin. This encapsulation helps to prevent moisture to penetrate and to affect the winding material. This type of transformer is available in ratings of 25 kVA to 12.5 MVA with insulation class of F (155°C Temp. Rise).

- **Vacuum pressure Impregnated Transformer (VPI):** in this type of transformer the primary and secondary windings are coated with a high-temperature, moisture-resistant polyester sealant. The polyester sealant is typically applied with a vacuum pressure impregnation process. This type of transformer is available from 5 kVA to 30 MVA with insulation class F (155°C) and H (180°C).

The dry type transformers don’t require practically any maintenance and they certainly have to be preferred in that environments where the risk of fire is high. In fact, oil type transformers require the development and maintenance of reliable fire safety measures: for transformers heavier than 500 kg an adequate oil-collection pit is required and for transformers with power higher than 1000 kVA is required the separation from other neighbouring transformers, building structures, and site equipment with suitable firewalls. Instead dry-type transformers can be located close to the electrical load, reducing, therefore, the cable costs and electrical losses. Dry-type transformers generally weigh less than equivalent oil-filled transformer, consequently the installation costs are lower. In addition, oil type transformer may require periodic sampling of the oil and more exhaustive maintenance procedures. However, although dry type transformers are advantageous, they are limited by size and voltage rating. Higher MVA ratings and voltage ratings may require the use of oil transformers alone.
Transformers are classified according to the cooling method. For oil-filed transformers, there are two cooling fluids: the oil inside the transformer tank, in contact with the windings, and the external fluid, for which demineralized water is usually used. The circulation of the fluids can be natural or forced. In cast resin transformer the cooling fluid is only the external one, and in most cases, it is air.

Transformers of the conversion groups could have different kVA ratings depending on the power of the rectifiers. For rectifier diodes of 3.6 MW a transformer of 4 MVA is chosen, instead for rectifier diodes of 5.4 MW a transformer of 5.75 MVA is chosen. Almost always the power transformers used in TPSS are three windings transformer, in which the primary winding has a star connection, instead, as concerns the two secondary windings, one is wye connected, while the other is delta connected (Yyd11). The star point of the windings is not grounded.

This configuration allows us to obtain, on the secondary windings, voltages which are displaced by 30 electrical degrees. Thus, using this configuration, we can use a twelve-pulse rectifier to convert AC current into DC current. To control the output voltage of the conversion groups, power transformers are usually equipped with fully electronic on-load tap-changers (OLTCs). The OLTC changes the ratio of a transformer by adding or subtracting a number of turns from the primary or the secondary winding, thus OLTC enables voltage regulation by varying the transformer ratio under load and without interruption. A peculiarity of the transformers used in traction substations consists on the short circuit voltage which is comprised between 5% and 12%. These values are much higher than the values find for the power transformers used for the normal distribution. The reason lies in the fact that the power transformers used in TPSS are subjected to many more short circuits with respect to other power transformer. Therefore, they should tolerate better and try to reduce the effects of overcurrents, which means increasing the leakage reactance of the transformer. On the other hand, an increase of the leakage impedance implies an increase in the transformer losses and in the voltage drops, with negative consequences on the supply of the contact line. For this reason, transformers with short circuit voltage around 10% are usually chosen.

**AC/DC CONVERTERS**

The first types of AC to DC conversion systems used were the rotating converters, but the invention of the mercury arc rectifier in 1902 replaced the rotating converter, which was well known to be inefficient and required much maintenance. Nowadays silicon diodes are exploited since they are more reliable, required less maintenance and they allow to realize high power conversion units with small dimensions. However, they suffer overloads and they are very sensible to overvoltage, therefore they must be protected from short circuits and...
over-voltages. The protection against internal short circuits is ensured by the circuit breaker of the transformer while the protection against external short circuits is obtained with a high-speed circuit breaker placed on the DC line. As concerns the protections against overvoltage, capacitor banks, surge protection devices and arrests are used to protect the rectifier against overvoltage.

Let’s analyse now the three-phase, six-pulse, full bridge diode rectifier shown in figure 2-7. We will begin the analysis with the idealized circuit in which $L_s = 0$ and the DC side is replaced by a constant dc current $I_d$.
The current $I_d$ flows through one diode from the top group and through one from the bottom group. In the top group, the diode with the highest anodic potential will conduct and the other two become reverse biased. In the bottom group, the diode with the lowest cathodic potential will conduct and the other two become reverse biased.

Figure 2-8a shows the voltage waveforms in the analysed circuit, where $v_{pn}$ is the voltage at the point P with respect to the ac voltage neutral point n. Similarly, $v_{nn}$ is the voltage at the negative dc terminal N.

Since $I_d$ flows continuously, at any time, $v_{pn}$ and $v_{nn}$ equal one of the ac input voltages $v_{an}, v_{bn}$ and $v_{cn}$.

Applying KVL, we can obtain the dc-side voltage which is shown in figure 2-8b:

$$v_d = v_{pn} - v_{nn} \quad (2.1)$$

In one period of the line-to-line voltage, $v_d$ consists of six segments and each segment belongs to one of the six line-to-line voltage combinations. This is the reason why this rectifier is often termed a six-pulse rectifier.

Each diode conducts for $120^\circ$. Considering the waveform of current in the phase a:

$$l_a = \begin{cases} 
I_d & \text{when diode 1 is conducting} \\
-I_d & \text{when diode 4 is conducting} \\
0 & \text{neither diode 1 or 4 is conducting}
\end{cases} \quad (2.2)$$

The commutation of current from one diode to the next is instantaneous since we assumed $L_s = 0$. 


Therefore we find the waveforms of the phase currents which are shown in figure 2-8c.

Let’s compute the average value of the output dc voltage and the rms values of the line currents.

To obtain the average value of the output dc voltage, we can consider only one of the six segments and obtain its average over a 60° interval. The time origin $t = 0$ is chosen when the line-to-line voltage $V_{ab}$ is at its maximum. Therefore:

$$v_d = v_{ab} = \sqrt{2}V_{LL}\cos \omega t \quad \frac{-\pi}{6} < \omega t < \frac{\pi}{6}$$  \hspace{1cm} (2.3)

where $V_{LL}$ is the rms value of line-to-line voltages.

By integrating $v_d$ in the interval $-\frac{\pi}{6} < \omega t < \frac{\pi}{6}$ we obtain the area $A$, shown in figure 2-8b:

$$A = \int_{\pi/6}^{\pi/6} \sqrt{2}V_{LL}\cos \omega t \ d(\omega t) = \sqrt{2} V_{LL}$$ \hspace{1cm} (2.4)

Thus, dividing $A$ by the $\pi/3$ interval yields:

$$V_{d0} = \frac{1}{\pi/3} \int_{\pi/6}^{\pi/6} \sqrt{2}V_{LL}\cos \omega t \ d(\omega t) = \frac{3}{\pi} \sqrt{2} V_{LL} = 1.35V_{LL}$$ \hspace{1cm} (2.5)

In the reality, there are not only three diodes in each commutating group, because the diode has a maximum reversed voltage which is lower than the output voltage, so when the diode is not conducting the potential on the diode is too high and the diode cannot tolerate it. To
solve this problem, it is necessary to put in series a certain number of diodes for each branch of the bridge. Over time, thanks to the development of power electronic devices, we moved from a configuration with 216 diodes to a configuration with only 30 diodes. This connection ensures a protection against overvoltages and the redundancy of the elements of the converter.

![Diagram of diode configurations](image)

*Figure 2-9: configurations of the Graetz bridge with time.*

The rms value of the ac line current $i_s$, in this idealized case, is found using the definition of rms current in the phase current waveform:

$$i_s = \sqrt{\frac{2}{3}} I_d = 0.816I_d$$  \hspace{1cm} (2.6)

By means of the Fourier analysis of $i_s$ in the ideal case, the fundamental component $i_{s1}$ has a rms value is equal to:

$$i_{s1} = \frac{\sqrt{6}}{\pi} I_d = 0.78I_d$$  \hspace{1cm} (2.7)

The currents absorbed from the network ($i_s$) have a rectangular waveform. This means that in addition to the fundamental harmonic ($i_{s1}$) there are also higher harmonics ($i_{sh}$). The generic harmonic component $h$ can be expressed as:

$$i_{sh} = \frac{i_{s1}}{h}$$  \hspace{1cm} (2.8)

Since $i_{s1}$ is in phase with its phase voltage, as shown in figure 2-12, even harmonics are nil as well as third harmonic and its odd multiple.
Figure 2-10: line current in a three-phase rectifier in the idealized case with $L_s = 0$.

Figure 2-11: analysis of the harmonics of the line current.

The sizing power of the transformer is:

$$A = 3EI = \sqrt{3}V_{LL}I = \sqrt{3} \frac{\pi}{3\sqrt{2}} V_{d0} \sqrt{\frac{2}{3}} I_d = \frac{\pi}{3} P_{d0} = 1.05P_{d0} \quad (2.9)$$

This equation means that the transformer and the lines must be designed for an apparent power which is higher than the real power delivered to the system. This fact is due to the presence of harmonics, which, increasing the rms of the current, add some losses.

Now we will include $L_s$ on the AC side, so that the current commutations will not be instantaneous. The DC side is still represented by a current source $i_d = I_d$. 

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Since the time origin is chosen arbitrarily, let’s consider that the commutation of current from diode 5 to diode 1 begins at $\omega t = 0$. Therefore, before the start of the commutation, the current is flowing through diodes 5 and 6. Figure 2-15a shows the circuit related to this commutation.

The current commutation involves only phase a and c, thus the commutation voltage is:

$$v_{\text{comm}} = v_{an} - v_{cn} \quad (2.10)$$

We introduce the two mesh currents $i_u$ and $I_d$. We can conclude that the phase currents are:

$$i_a = i_u \quad (2.11)$$

And
\[ i_c = I_d - i_u \]  \hspace{1cm} (2.12)

In figure 2-13b the phase currents are plotted. \( i_u \) increases from zero to \( I_d \), this last value is reached at the end of the commutation interval \( \omega t = u \).

Let us compute the voltage drop \( v_{La} \) and \( v_{Lc} \):

\[ v_{La} = L_s \frac{di_u}{dt} = L_s \frac{di_u}{dt} \]  \hspace{1cm} (2.13)

and

\[ v_{Lc} = L_s \frac{di_c}{dt} = -L_s \frac{di_u}{dt} \]  \hspace{1cm} (2.14)

Applying the KVL in the upper loop of the circuit and using the above equations, we find:

\[ v_{comm} = v_{an} - v_{cn} = v_{La} - v_{Lc} = 2L_s \frac{di_u}{dt} \]  \hspace{1cm} (2.15)

therefore:

\[ L_s \frac{di_u}{dt} = \frac{v_{an} - v_{cn}}{2} \]  \hspace{1cm} (2.16)

The commutation interval \( u \) can be obtained by multiplying both the sides of the above equation by \( \omega \) and integrating:

\[ \omega L_s \int_0^{I_d} di_u = \int_0^{u} \frac{v_{an} - v_{cn}}{2} d(\omega t) \]  \hspace{1cm} (2.17)

Where the time origin is assumed to be at the beginning of the current commutation. With this choice of time origin, we can express the line-to-line voltage \( (v_{an} - v_{cn}) \) as:

\[ v_{an} - v_{cn} = \sqrt{2} V_{LL} \sin \omega t \]  \hspace{1cm} (2.18)

Substituting the expression of \( v_{an} - v_{cn} \) in the integral we get:

\[ \omega L_s \int_0^{I_d} d i_u = \int_0^{u} \frac{\sqrt{2} V_{LL} \sin \omega t}{2} d(\omega t) \]  \hspace{1cm} (2.19)

\[ \omega L_s I_d = \frac{\sqrt{2} V_{LL} (1 - \cos u)}{2} \]  \hspace{1cm} (2.20)

\[ \cos u = 1 - \frac{2 \omega L_s I_d}{\sqrt{2} V_{LL}} \]  \hspace{1cm} (2.21)

During the interval \( 0 < \omega t < \omega t_u \), the voltage \( v_{pn} \) equals:

\[ v_{pn} = v_{an} - L_s \frac{di_u}{dt} = \frac{v_{an} + v_{cn}}{2} \]  \hspace{1cm} (2.22)

Where the voltage across \( L_s \) is the drop in the voltage \( v_{pn} \) during the commutation interval. The integral of this voltage drop is the area \( A_u \) which equals:

\[ A_u = \omega L_s I_d \]  \hspace{1cm} (2.23)

This area is lost every 60° interval, as shown in figure 2-14.
Therefore, the voltage drop due to the commutation is:

$$\Delta V_d = \frac{3}{\pi} \omega L_s I_d$$  \hspace{1cm} (2.24)

We can now write the average rectified voltage $V_d$ which is obtained subtracting to the theoretical rectified voltage $V_{d0}$ the voltage drop $\Delta V_d$:

$$V_d = V_{d0} - \Delta V_d = 1.35V_{L0} - \frac{3}{\pi} \omega L_s I_d$$  \hspace{1cm} (2.25)

The output voltage contains a ripple, which means that there are some harmonic components on the voltage. If these components are high they can create interferences with the signalling systems, thus they can worsen the quality of the signals transmitted. A good solution, to reduce the ripple of the DC output voltage, would be to use a twelve-pulse rectifier, instead of a six-pulse rectifier. As said before, the power transformer of the conversion group is a three-winding transformer and one of the two secondary windings is wye connected, the other is delta connected. This means that the two secondary voltages are displaced by 30°. To obtain a twelve-pulse rectifier a three-winding transformer and two three phase Graetz bridges are necessary, and each of the two secondary windings are connected to one of the two three phase Graetz bridges. Finally, the connection of the two Graetz bridges can be a series or a parallel connection.

**SERIES CONNECTION:** Generally, the series connection is not widely used because a fault in one bridge would result in the out of service of the complete system.
The current which passes through the two six pulse rectifiers is the same and the voltage at the external terminals is the sum of the voltages at the terminals of the two Graetz bridges, which are displaced by 30°. In particular, in the interval $0 < \omega t < 30^\circ$, we obtain:

$$v_{d1} = \sqrt{6} \cdot V_f \cdot \cos \omega t \quad v_{d2} = \sqrt{6} \cdot V_f \cdot \cos \left( \omega t - \frac{\pi}{6} \right)$$

(2.26)

Where $v_{d1}$ is the output voltage of the upper bridge and $v_{d2}$ is the output voltage of the lower bridge. Therefore, the output voltage of the whole twelve pulse rectifier will be:

$$v_d = v_{d1} + v_{d2} = \sqrt{6} \cdot V_f \cdot \cos \frac{\pi}{12} \cdot \cos \left( \omega t - \frac{\pi}{12} \right)$$

(2.27)

$$V_{dmax} = 2 \cdot \sqrt{6} \cdot V_f \cdot \cos \frac{\pi}{12} = 2 \cdot \sqrt{6} \cdot V_f \cdot \frac{\sqrt{6} + \sqrt{2}}{4} = 4.732 V_f$$

(2.28)

$$V_{dmin} = 2 \cdot \sqrt{6} \cdot V_f \cdot \cos \left( -\frac{\pi}{12} \right) = \left( \sqrt{6} + \frac{3\sqrt{2}}{2} \right) \cdot V_f = 4.571 V_f$$

(2.29)

$$\frac{V_{dmax}}{V_{dmin}} = 1.035 V_f$$

(2.30)

From the last equation, we can notice that the voltage variation is smaller with respect to the one of six-pulse rectifier; in fact, the voltage oscillation passes from the 15% to the 3.5% of the average value and this results also in a reduction of the harmonic content of the output voltage.
In a twelve-pulse rectifier, the pulse number \( q_v \) is equal to 12; therefore, the average value of the output voltage results:

\[
V_{d0} = \frac{q_v}{\pi} \cdot V_{dmax} \cdot \sin \frac{\pi}{q_v} = \frac{12}{\pi} \cdot (3 + \sqrt{3}) \cdot V_f \cdot \sin \frac{\pi}{12} = 4.678 \cdot V_f
\]  
(2.31)

Let’s compute now the transformation ratios:

\[
k_{T,Y} = \frac{V_{12}}{V_{1'2'}} = \frac{N_1}{N_2} = k_s
\]  
(2.32)

\[
k_{T,Yd} = \frac{\sqrt{3}V_{19}}{\sqrt{3}E_1} = \frac{\sqrt{3}E_{1'}}{E_{1'}} = \frac{\sqrt{3}N_1}{N_2} = \sqrt{3}k_s
\]  
(2.33)

If we want to maintain the same transformation ratio for the secondary winding delta connected, it should have a number of turns equals to three times the number of turns of the other secondary winding star connected.

**PARALLEL CONNECTION:** The parallel connection is intrinsically redundant; therefore, it is the most adopted solution. In this type of connection, the output voltages of the two bridges are equal in amplitude and displaced by 30°, thus it is not possible connect these bridges directly because the current would not be equally divided between the two bridges. The parallel connection requires consequently the insertion of an inductance between the two bridges that absorbs the difference between their instantaneous output voltages and distributes the load equally.

\[\text{Figure 2-16: parallel connection of two six pulse rectifiers.}\]
The output voltage of the twelve-pulse rectifier will be:

\[
v_d = \frac{v_{d2}}{2} + \frac{v_b}{2} = v_{d2} - \frac{v_{d2} - v_{d1}}{2} = \frac{v_{d1} + v_{d2}}{2}
\]  
(2.34)

\[
V_{dmax} = \sqrt{6} \cdot V_f \cdot \frac{\sqrt{6} + \sqrt{2}}{4} = \frac{3 + \sqrt{3}}{2} \cdot V_f = 2.366 V_f
\]  
(2.35)

In the same way, also \(V_{dmin}\) will be half of the previous case. Therefore, the ratio \(\frac{V_{dmax}}{V_{dmin}}\) will remain equal. The average value of the output voltage results:

\[
V_{d0} = \frac{q_v}{\pi} \cdot V_{dmax} \cdot \sin \frac{\pi}{q_v} = \frac{12}{\pi} \cdot \left(3 + \sqrt{3}\right) \cdot V_f \cdot \sin \frac{\pi}{12} = 2.34 \cdot V_f
\]  
(2.36)

It is half of the case with series connection. Anyway, in both type of connections, the result is that the output voltage has twelve pulses in one period, therefore the harmonic content has been reduced.

Finally let’s summarize the advantages and disadvantages of the series connection.

If the series connection is used the following advantages are met:

- Less sensitivity to the imbalance between the secondary windings of the group transformer.
- Values of not characteristic harmonics, for example 5° and 7°, lower than those found with the parallel connection.
- No need to use the inductance to connect the two bridges.
- Lower values of short circuit currents.

On the other hand, in the series connection we have the disadvantage of having much higher load losses (about twice that of the parallel connection); in addition, the series connection is not intrinsically redundant because if one bridge fails, the entire system goes out of service.
In any Graetz bridge special attention should be paid to the cooling of the diodes, which are mounted on an air-cooled heatsink having adequate heat dissipation properties. Such diode with double-side heatsink creates a diode module. Each diode module is protected with a RC circuit, this is known as snubber circuit.

Two disadvantages of the Graetz bridge rectifier are:

- The Graetz Bridge is unidirectional: the power can flow only from the AC side to the DC side;
- Diodes are not controllable switches; thus, it is not possible to have a controlled DC output.

Some manufactures propose to use a thyristor bridge to overcome these two problems. In fact, the turn on the thyristor can be controlled by a gate current so that it is possible to choose the instant of commutation and then control the DC output. In addition, since the thyristor can block voltage in both directions, it is possible to reverse the polarity of the output dc voltage and hence feed power back to the ac supply from the dc side. This means that the thyristor bridge is bidirectional: power can flow from AC to DC side and vice versa.

As shown in figure 2-18, the electric scheme of the thyristor bridge is the same of the Graetz bridge, the only difference is that the thyristor bridge uses thyristors instead of diodes:

If the gate currents were continuously applied, the thyristors would behave as diodes. Under these conditions ($\alpha = 0$ and $L_s = 0$) the output voltage would be:

$$V_{d0} = \frac{3\sqrt{2}}{\pi} V_{LL} = 1.35V_{LL}$$  \hspace{1cm} (2.37)
Considering the commutation of current from thyristor 5 to 1. As said before, the instant of commutation can be controlled and hence let’s assume that it is delayed by an angle $\alpha$. Therefore, thyristor 5 keeps on conducting until $\omega t = \alpha$. So, in general the turn on of the second thyristor is delayed by an angle $\alpha$ which corresponds to the time $t = \alpha/\omega$.

It is now possible plot the effect of the delay angle $\alpha$ on the converter waveforms and the dc output voltage $V_{d0\alpha}$:

For the thyristor bridge the average output DC voltage is:

$$V_{d0\alpha} = V_{d0} \cos \alpha \quad (2.38)$$

We can notice from the above equation that the DC side voltage is a function of the delay angle $\alpha$. The maximum value that $\alpha$ can assume is 180°. From the figure 2-21 we can conclude that if $\alpha$ is between 0° and 90°, $V_{d0\alpha}$ is positive and the power flows from the AC side to the DC side; instead if $\alpha$ is between 90° and 180°, $V_{d0\alpha}$ is negative and the power flows from the DC side to the AC side.
We can conclude that the thyristor bridge can work as a rectifier or as an inverter, depending on the value of $\alpha$, in other words depending on the power flow:

![Figure 2-21: DC side voltage as a function of $\alpha$.](image)

![Figure 2-22: normalized DC voltage as a function of $\alpha$.](image)
As said before, the thyristor bridge solves some problems of the diode bridge. Despite that this solution is not widely used because of the following disadvantages:

- Since the thyristor is a controllable switch an external control for the angle $\alpha$ is needed and this means that it is necessary to add other components which can fall and hence decrease the reliability of the system.
- The ripple of the DC output voltage is increased with respect to the diode bridge. Therefore, the harmonic content is increased too.
- The absorbed reactive power, which depends on the angle $\alpha$, could be too high, thus the power factor decreases and reactive power compensation is necessary.
- To reverse the flow of the power the connections must be changed.
- More expensive than the diode bridge.

A new type of rectifier used in some recent TPSS is the IGBT bridge. This type of converter has several advantages:

- Regulating voltage without ripples. Therefore, the harmonic content is low, and the quality of power is high in both the AC and DC side.
- Reversing the flow of power without change the connection of the terminals.
- Operation with high power factor.

The output of the rectifier is connected to a filter composed by a big reactor (6–9 mH) in series with the positive DC busbar and a shunt capacitor bank connected to the positive and negative DC bus bars. The shunt capacitor bank is divided in three sections, each one

*Figure 2-23: IGBT bridge.*
containing four capacitors of 40 \( \mu F \). The purpose of the filter is to reduce the harmonics generated by the rectifier, in order to avoid interferences in the nearby telecommunication lines and security installations.

### 2.3.3 DC side

The DC side is formed by:

- A negative and a positive DC busbar.
- A sequence of protection devices such as DC disconnectors and high-speed DC circuit breaker.

The negative busbar is connected directly to the rail while the positive DC busbar is connected to the contact line through a sequence of protection devices.

The DC circuit-breakers are used to protect the contact line or the third rail powering the vehicles. The DC circuit breakers are different from those used in AC side, this is due to the fact that with alternating current there is natural passage of current through zero at each half cycle, which corresponds to the quenching of the arc during the circuit opening. Instead, with direct current, there is not such natural passage and therefore, to guarantee arc extinction, the current must decrease to null (forcing the current passage through zero). Therefore, to guarantee the arc extinction in a very short time, the circuit breakers used in the DC section are high-speed current limiting circuit-breakers (extra-rapid circuit breakers), and hence they are more expensive than the circuit breakers used in the AC section.

A surge arrester is connected to each DC circuit breaker, it is used to protect the electrical equipment of the TPSS from over-voltages (lightning strokes) occurring on the contact line.

![Figure 2-24: horn gap disconnector.](image)

The particular type of disconnector, shown in figure 2-24, is used at the exit of the TPSS, to ensure the sectioning of the catenary at \( 3 kV_{cc} \).
2.4 TPSS power supply

The fundamental parameter to size correctly the distance between two electric conversion substations is the power absorbed by the vehicles in the considered section, this means, in turn, that to choose the distance we need to know the type of vehicles and the traffic. In subway, which provides an urban service and operates with lower values of voltages with respect to the railway, the average distance between two consecutive substations is very limited, for example, in a 750 V high traffic subway it can be in the order of 1.5 km. On the contrary for the railways system, in the past, the distance between the various TPSS was between 35 and 45 km. Nowadays, the distance is decreased to 15-20 km since the traffic is increased.

The TPSS can be connected to the three-phase industrial network in different ways. It can be supplied directly from the industrial grid, and in this case, it is connected to a station of the industrial network, as shown in figure 2-25; but since it is not always possible to connect directly the TPSS to the high voltage stations of the industrial grid (these stations are not present in all the areas in which a connection is require), in this case the TPSS is fed by dedicated primary lines. Anyway, in both the cases the power supply is called homogeneous.

![Figure 2-25: direct power supply from the industrial grid.](image)

Finally, the TPSSs of the traction system can be connected to both the industrial grid and primary lines, in this case we talk about heterogeneous power supply.
In the above figure, we can notice that the TPSS 6 and 9 have heterogeneous power supply. Instead, the TPSS 7 and 8 are supplied only by the primary lines.

The TPSS can be inserted in series or in parallel on the primary line.

Figure 2-26: different types of power supply for the TPSS.

Figure 2-27: shunt connection of an TPSS.
Figure 2-27 shows an example of shunt connection. In this case the TPSS can be fed by only a primary line. Therefore, the simplicity of installation has been preferred with respect to the continuity of operation.

Figure 2-28: series connection of an TPSS, with double HV bus-bars arrangement.

With this configuration, the TPSS can be powered by one of the two primary lines or both, thus this kind of connection ensures the continuity of operation in case of failure of one of the two sections.

As concerns the TPSS bus-bars, they are a very important part of the TPSS structure since they carry high amount of energy in a confined space and their failure would be very severe on the power supply continuity. Therefore, the bus system must be built to be electrically flexible and reliable enough to ensure a continuous service. The choice of the bus arrangements depends on the system voltage, on the position of substation in electrical power system, on the flexibility needed in system and cost to be expensed. Single Bus System is the simplest and the cheapest one. As the name suggests, it consists of a single bus-bar and all the incoming and outgoing lines are connected to it.

The main advantages of this type of arrangement are low initial cost, less maintenance and simple operation. However, the principal disadvantage of single bus-bar system is that if repair is to be done on it or a fault occurs, there is a complete interruption of the supply.
Instead a double bus-bar system consists of two identical bus-bars, separated by a bus coupler. All the outgoing or incoming lines can be taken from any of the two buses. In fact, every line is connected to both buses in parallel through an individual isolator. By closing any of the isolators one line can be associated to one of the two buses. All the buses are energized...
and the outgoing lines are divided into two groups, one group is fed from one bus and the other group is fed from the second bus. But any feeders, at any time, can be transferred from one bus to the other. There is one bus coupler breaker which should be kept close during bus transfer operation. Therefore, double bus-bar arrangement increases the flexibility of system; but the presence of a second bus bar increases also the cost of installation and maintenance.

![Diagram](image)

*Figure 2-31: series connection with double bus-bar arrangement.*

### 2.5 Contact line

The current is transmitted from the traction substations to the vehicles through the overhead contact line system which is therefore the positive conductor of the system. Both mechanical and electrical considerations have to be made to choose the material and the cross section of the contact wire. The most common material used for the contact wire is copper, either a solid wire or stranded wire and sometimes with alloy additives. For certain applications, copper alloy conductors are preferred instead of pure copper, especially when higher strengths or corrosion resistance properties are required. The different parts of the overhead contact lines are: contact and messenger wires, droppers and support poles.
The messenger wire is connected to the contact wire by droppers. The messenger wire has an electric function besides its mechanical function since it is used to carry the current as well. In fact, all the wires are made of copper, so the total cross section is the sum of the cross-section areas of contact and messenger wires. The contact and messenger wires are not connected electrically together through droppers, because droppers are light connections that have only a mechanical function and they are not designed to carry high currents. Instead, this electrical connection is realized with a strong short circuit wire made of copper.

If a better current collection is required, an additional wire can be used at each support structure terminated on either side of the messenger wire (stitched catenary). Instead, when a very high current has to be collected the best solution is to use the compound catenary; which uses a second support wire, known as the "auxiliary", between the messenger and contact wire, and additional droppers support the contact wire from the auxiliary. The auxiliary wire can be made with a more conductive but less wear-resistant metal. Since the auxiliary wire increases the number of wires which carry the current, the current becomes more uniform. The disadvantages of the compound catenary consist in the higher costs required for installation and maintenance.
The overhead catenary is supported by masts and cantilevers. Mast is a tall pole on which the cantilever is hung. The masts should be connected to each other using parallel grounding conductors.

Cantilever is a horizontal and long piece of metal which supports the catenary and projecting from a single mast on one side of the track. It is composed by different metal arms. The cantilever can be energized by the contact wire or connected to the ground. If it is energized the insulators must be put between the cantilever and the mast. On the other hand, if it is grounded the insulators have to be inserted between the cantilever and messenger and contact wires.

The line circuit, consisting of the contact line and the rails, is divided into several sections for operation, maintenance and protection purposes, in each section, for safety reasons, only a few trains are allowed to run at the same time.

Sections can be fed and disconnected by switches and disconnectors according to the following denomination:

- Segments are powered to one or both ends through automatic circuit breakers.
- Secondary segments are supplied by simple manual or remote disconnectors or with remote circuit breakers but not with automatic opening.
If the segment is between and supplied by two TPSS, then we are in presence of a double side power supply; if the contact line is supplied by only one TPSS we speak of single side power supply. Double side power supply has some advantages, for example with the double side power supply there is a reduction in the average voltage drop along the contact line, which is advantageous in terms of efficiency.

As said before the overhead lines are made of the copper wires; the resistivity of the copper is:

\[ \rho = 17.6 \frac{\Omega \cdot mm^2}{km} < 18 \frac{\Omega \cdot mm^2}{km} \]  

Thus, the resistance of the overhead line in Ω/km can be obtained:

\[ r_c = \frac{\rho}{A_c} \]  

Where \( A_c \) is the total cross section of the overhead conductor expressed in \( mm^2 \). We know that due to the friction between the pantograph and the contact wire part of the copper is
removed and hence the total cross section is reduced. To take into account this reduction the resistivity is slightly increased to the value of 18.

Therefore, the final resistance of the overhead line can be found with the following formula:

\[ r_c = \frac{18 \frac{\Omega}{km}}{A_c} \]

(2.41)

### 2.6 Return circuit and stray currents

Traction current is supplied to locomotive through the catenaries by traction substation and returns to traction substation through the rail which is both the running rail and the return current conductor. This solution has been chosen for its economic advantage, since it does not require the installation of an additional return conductor.

As the traction return current flows through the running rails, there will be voltage drops along the running rails due to the rail resistance. The value of the voltage drop can be computed with the following formula:

\[ V_{rail} = r_{rail} \cdot d \cdot I_{rail} \]

(2.42)

where:

- \( r_{rail} \) is the rail resistance per unit length,
- \( d \) is the distance of the train from the TPSS,
- \( I_{rail} \) is the current which returns to the TPSS through the rails.

Looking the previous equation, it is easy to understand that the rail voltage is maximum when the train is in the halfway point of the line between two TPSSs; since the distance \( d \) among the train and the substation reaches its maximum.

To compute the resistance of the rail the linear mass is used instead of the cross section. If we consider the classical steel rails, the linear resistance in \( \Omega/km \) results:

\[ r'_{rail} = \frac{0.75}{m} \]

(2.43)

Where \( m \) is the linear mass of the rail expressed in kg/m. To reduce the interferences of different signals and systems some disconnections are introduced in the rail; but to maintain the electric continuity the different sections must be connected by external connections which increase the resistance of the rail since they have smaller cross sections with respect to the cross section of the rail. To take into account this effect, the resistance in \( \Omega/km \) should be computed with the following expression:

\[ r_{rail} = \frac{0.9}{m} \]

(2.44)

Clearly, a high resistance of the running rail will force parts of the current to deviate from the intended path, the rail, and enter the earth and flow through the lower resistance of
neighbouring metallic infrastructures. These leakage currents are known as stray currents. The stray currents can cause corrosion with subsequent damage of metallic structures in the railway environment. Overheating, arcing and fire are further potential risks due to the stray currents with subsequent dangerous potential for people.

The problems caused by stray currents can be ameliorated using two different methods:
- Passive protection
- Active (Cathodic) protection

Passive protection is obtained with several methods:
  i. Insulating the rail from the soil. The insulation of the rail is made by putting rubber plates between the rail and the sleepers. Since there are also metallic clips, which connect the rail to the sleepers, these clips should be insulated too.
  ii. Insulating the underground metallic structures with an insulating coating (rubber) in order to increase the resistance between soil and the pipe. The coating should not contain holes, otherwise the problem will be worse. In fact, in points where holes are present there will be a concentration of electric field that will damage the pipe strongly. Another solution could be to use plastic pipe since plastic is an insulated material. Inside tunnels, the metallic structure in which stray currents can flow are interrupted so that the electric resistance increases.
  iii. Creating a short circuit in the structure, all the metallic constructions are electrically connected to a common point to make all the metals equipotential.

The corrosion of the metallic structure starts when the potential of the metal is higher than the potential of the soil.

![Figure 2-36: stray current.](image)

To prevent this phenomenon cathodic protection can be used. This type of protection requires an external DC source, which is connected to the surface of the metal that is
intended to be protected. With this connection, the potential of the metallic structure can become negative with respect to the soil, thus corrosion can be avoided.

2.7 System grounding

To properly approach the subject of grounding, we should, as first thing, understand the differences between “equipment grounding” and “system grounding”. The term equipment grounding refers to grounding all the metallic equipment, which due to the failure of insulations or for accidental reasons, may be in contact with live conductors and hence become charged. Instead system grounding refers to grounding the track running rails which carry the negative return current.

The grounding system of a DC traction TPSS should be designed to satisfy two basic requirements:

1. Under normal system operation, the grounding system should minimize the DC stray currents and hence their corrosion effects on nearby metallic structures. This can be achieved by not making direct intentional electrical connection between the negative conductor of the system and the ground.
2. Under abnormal system operation, the system should be grounded by shorting the negative conductor to ground to eliminate the unsafe voltages. The rail should be shorted to the ground through protection relays and shorting devices in a time which is as short as possible.

There are many types of grounding systems schemes with which the TPSS could be grounded. These schemes are discussed below:

A. Undergrounded system: this type of system operates without intentional connection to earth ground. Its main advantage is that it offers the least value of stray currents; however, this type of system also offers some big disadvantages such as the difficulty in locating a line-to-ground fault. This method is not used in railway systems for safety reasons, especially under abnormal fault conditions.

![Diagram of undergrounded system](image-url)

*Figure 2-37: undergrounded system.*
B. Solidly grounded system: the negative of each substation is directly connected to the local ground grid without any intentional impedance. With this configuration, the negative return circuit represented by the running rails becomes in parallel with the ground; thus, stray currents increase their corrosion effects on the underground utilities in vicinity of the tracks. For this reason, the modern systems do not employ such a grounding system.

![Diagram of Solidly Grounded System](Figure 2-38: solidly grounded system)

C. Automatic Grounding switch: when the set voltage level is detected, the overvoltage relay device 59 actives and closes the shorting switch device 57 in order to ground the negative system; but it should be remembered that that a shorting switch is a mechanical device which takes time to activate and hence unsafe voltages could be reached during this time. On the other hand, if the overcurrent relay 50 detects a short circuit current, it activates and de-energizes the TPSS.

![Diagram of Automatic Grounding Switch](Figure 2-39: automatic grounding switch)

D. Diode grounded system: this configuration employs a parallel array of diodes with a shorting dc contactor and protection relays. As in the automatic grounding switch, when the set level of voltage is reached, the relay device 59 energizes the dc contactor, which automatically grounds the system. Instead the directional
overcurrent relay device 32 opens the dc contactor for low level of forward currents and trips the TPSS if high level ground fault current continues to flow. It should be noted that for small magnitudes of voltage difference between the rail and the ground the diodes are always conductive, therefore the system could result grounded also in normal system operation. This leads to high values of stray currents.

![Figure 2-40: diode grounded system.](image-url)

E. Thyristor grounding method: the overvoltage relay device 59 checks the negative-to-ground voltage. If this voltage exceeds a pre-set value, the relay triggers the thyristor gate by the auxiliary relay device 59X and the system is grounded, so that the dangerous rail-to-ground voltage is limited. The instantaneous current relay device 50 energize the time delay auxiliary relays 50X1 and 50X2. After a short delay if there is a decrease in the current, device 50X1 provides an alarm and the gate turn off signal to the thyristor to resume its normal position of an ungrounded system. However, if the current continues to flow in case of positive-to-ground fault, then after a pre-set time delay device 50X2 will trip all dc feeder breakers. The pre-set voltage value of the relay device 59 can be set about 60 V, which is considered a safe touch potential. The advantage of the bi-directional thyristor scheme over the grounding diode scheme is that the thyristor unit will ground the system only when the set dangerous voltage occurs. Under normal system operation, below the set negative-to-ground overvoltage, the system is kept ungrounded.
Let’s summarize the types of grounding systems schemes above described with a table:

<table>
<thead>
<tr>
<th>System Grounding Method</th>
<th>Rail-to-Ground Potential (Vehicle Touch Potential)</th>
<th>Stray current level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solidly Grounded</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Diode Grounded</td>
<td>Moderate/Low</td>
<td>Moderate/High</td>
</tr>
<tr>
<td>Thyristor Grounded</td>
<td>Moderate/High</td>
<td>Moderate/Low</td>
</tr>
<tr>
<td>Ungrounded System</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

From the safety point of view running rails should be grounded, however, from the stray current point of view they should be kept isolated from ground. To satisfy both the requirements, the system grounding scheme should ground the rail if dangerous voltage difference between the rail and ground are detected, and automatically return to the normal state of an ungrounded rail when dangerous voltage is suppressed. To achieve this purpose the preferred solutions are the thyristor and the diode grounding methods.

### 2.8 Equipment grounding

To ground all the metallic structures and the supports which could enter in contact with the live conductors, and hence to protect the people and installations in case of insulation fault, a protection circuit must be created. It is composed by an earth wire and by earth electrodes; The wire is made of two aluminium ropes, each rope has usually a cross section of about 125 mm². The earth wire connects all the supports and metallic structures among themselves. Instead, the electrical connection with the earth is provided by the earth electrodes. The structure of the ground circuit requires that the connection of the supports between them with the earth wire be divided in sections of 3 km. All the supports of each section must be connected to an earth electrode, whose value must be lower than 2 Ω.
Each end of the section is connected through a diode to the two rails of the nearest track; in case of normal operation the ground circuit is separated from the rails to avoid that the dc current disperses in the ground, causing the corrosion, instead in case of fault the diode conducts, and the ground circuit is connected with the running rail.

In any case, all the protective provisions relating to electrical safety and earthing can be found in the Standard CEI EN 50122-1.
CHAPTER 3
PROTECTIONS DEVICES

3.1 Protection Scheme

The protection devices installed in the TPSSs must:

- contribute to the safe detection of faulty elements of the electrical system and to their consequent exclusion, in order to speed up the diagnosis of the fault and the restarting of the service;
- be appropriately coordinated;
- be properly maintained; in fact, in case of malfunction of the TPSS protection system the distributor has the right to ask for a system review and immediate corrective actions.

The protection scheme used for DC power supply is very much different from the more common protection schemes that are used in AC power supply. The design of the DC traction protection scheme is more complex as it takes into consideration various aspects. It is essential that the protection system recognize the difference between normal and fault operation and the several types of faults. In addition, the protection system should remove only the faulty section from the network in order to minimize the impact of the fault on the overall system.

The EN 50123 series requires that DC switchgear is subjected to a series of tests which normally includes short circuit obligations, electrical and mechanical endurance analysis, temperature rising testing, dielectric testing. Obviously, each type of test is subject to variation depending on the type of circuit breaker to be tested, the system voltage and the characteristic of the system which is being switched.
In this chapter, we will describe all the type of protections used in the protection scheme of DC traction systems; but, first of all we have to define the types of fault which can happen in these systems.

### 3.2 Types of fault

The different types of fault that can happen in a DC traction system are the following:

1) ground fault in the substation: this fault can happen because of a fault on the DC side of the converter and it involves the exposed conductive parts that are connected to the grounding system of the substation;

2) short circuit in the substation: short circuit faults near the substations cause the highest fault currents, in fact, with this type of fault the extra-rapid circuit breaker will certainly interrupt the fault current, since the relay will certainly recognize the fault;

3) fault to a pole along the line: this type of fault is not very common, because all the elements used to keep up the overhead catenary are made of insulating materials; anyway, if the fault happens it constitutes a ground fault since all the supports are

<table>
<thead>
<tr>
<th>EN</th>
<th>Equipment specified</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN 50123-1</td>
<td>Railway applications- Fixed installations-DC switchgear</td>
</tr>
<tr>
<td>EN 50123-2</td>
<td>Railway applications- Fixed installations-DC circuit breakers</td>
</tr>
<tr>
<td>EN 50123-3</td>
<td>Railway applications- Fixed installations- Indoor DC disconnectors, switch disconnectors and earthing switches</td>
</tr>
<tr>
<td>EN 50123-4</td>
<td>Railway applications- Fixed installations- Outdoor DC disconnectors, switch disconnectors and earthing switches</td>
</tr>
<tr>
<td>EN 50123-5</td>
<td>Railway applications- Fixed installations- Surge arresters and low voltage limiters for specific use in DC systems</td>
</tr>
<tr>
<td>EN 50123-6</td>
<td>Railway applications- Fixed installations- Measurement, control and protection devices for specific use in DC traction systems</td>
</tr>
<tr>
<td>EN 50123-7</td>
<td>Railway applications- Fixed installations-DC circuit breakers</td>
</tr>
<tr>
<td>EN 50124-1</td>
<td>Railway applications- Insulation coordination</td>
</tr>
</tbody>
</table>
connected to a grounding system, but once that the diode starts to conduct, connecting the running rail to the grounding system of the support, this ground fault turns into a short circuit.

4) short circuit along the line: it can happen on a vehicle or through a metallic structure connected to the return circuit and it should produce a fault current high enough to trigger the extra-rapid circuit breaker.

5) ground fault along the line.

![Figure 3-1: possible faults on DC traction system.](image)

When a short circuit happens in the substation, the fault current magnitude will be high enough to make the extra-rapid circuit breaker trip, but in case the short circuit happens outside the substation and far from it, for example on a vehicle, or in case of ground fault, the current would be limited by the circuit resistances, resulting in a current whose value is comparable with that of normal load current. In this case, dangerous voltages can arise and last for long periods without the intervention of any maximum current protection.

In general, the workers can be subject to risk of electric shock inside the substation, and people outside the substation, in case that a fault is not recognized and interrupted in a time interval shorter than that allowed by Standard EN 50122-1.

The maximum allowable effective touch voltages $U_{te,max}$ in dc traction systems as a function of time duration are reported in table 3-1. As it can be seen, if the circuit breaker does not trip, the maximum permissible effective touch voltage is 120V. If, instead, the circuit breaker recognizes the fault and trips, permissible voltages must be analysed depending on the fault duration and they can reach very high values such as 870V.

For short-term conditions, Standard EN 50122-1 considers an additional resistance of 1000Ω for the calculation of the effective touch voltage; this value is typically used to take into account the shoes of the considered person. If the time duration of the fault is below 0.7 s, the permissible effective touch voltages are much higher.
Table 3-2: maximum permissible effective touch voltages $U_{te,max}$ in DC traction systems as a function of time duration.

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>$U_{te,max}$ Long-term (V)</th>
<th>$U_{te,max}$ short-term (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;300</td>
<td>120</td>
<td>-</td>
</tr>
<tr>
<td>300</td>
<td>150</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>160</td>
<td>-</td>
</tr>
<tr>
<td>0.9</td>
<td>165</td>
<td>-</td>
</tr>
<tr>
<td>0.8</td>
<td>170</td>
<td>-</td>
</tr>
<tr>
<td>0.7</td>
<td>175</td>
<td>-</td>
</tr>
<tr>
<td>&lt;0.7</td>
<td>-</td>
<td>350</td>
</tr>
<tr>
<td>0.6</td>
<td>-</td>
<td>360</td>
</tr>
<tr>
<td>0.5</td>
<td>-</td>
<td>385</td>
</tr>
<tr>
<td>0.4</td>
<td>-</td>
<td>420</td>
</tr>
<tr>
<td>0.3</td>
<td>-</td>
<td>460</td>
</tr>
<tr>
<td>0.2</td>
<td>-</td>
<td>520</td>
</tr>
<tr>
<td>0.1</td>
<td>-</td>
<td>625</td>
</tr>
<tr>
<td>0.05</td>
<td>-</td>
<td>735</td>
</tr>
<tr>
<td>0.02</td>
<td>-</td>
<td>870</td>
</tr>
</tbody>
</table>

3.3 Overcurrent protection

The overcurrent relay provides protection for the conductor rails, feeder and substations for intermediate or remote overload conditions such as bolted faults, arcing faults and severe overloads. In overcurrent relay the controlled quantity is only current; it is generally used on the positive feeders in the traction network. The overcurrent relay is usually used in combination with an auto-reclose relay; the relay will send a signal to the extra-rapid circuit breaker to interrupt the fault if the current detected is higher than a pre-set value, then a line test will be carried out and if the network is healthy, the circuit breaker recloses to continue the service.

A pre-set current value $I_{max^+}$ and $I_{max^-}$ is set in the relay, which leads to the tripping of the circuit breaker. This limit value ($I_{max}$) is usually sets about 8÷8.5 kA for traction networks which work at 750 $V_{dc}$ instead is set at 4÷4.5 kA for traction networks working at 1500 $V_{dc}$.

The overcurrent relay has a total of three overcurrent protection functions that can independently trip the feeder breaker. The 3 different ways of detection are:

i) The overcurrent is detected by the tripping device of the circuit breaker and will automatically open and clear the fault (instantaneous characteristic).

ii) When the current flowing through the feeder exceeds the pre-set $I_{max}$ value during a certain pre-set time, then an opening order is given to the circuit breaker (definite-
time characteristic). The $I_{\text{max}}$ value is obviously lower than the breaker overcurrent tripping value. The $I_{\text{max}}$ value can be either positive ($I_{\text{max}+}$) or negative ($I_{\text{max}-}$).

iii) The tripping time of the relay decreases with the increases of the value of the current flowing through the feeder (inverse-time characteristic).

When electromechanical relays were still used, these three characteristics were achieved with separate relays. Instead, thanks to the introduction of solid-state protection relays, these characteristics can be combined into one device.

In general, if the current value exceeds the pre-set $I_{\text{max}}$ value but occurs within the duration of the pre-set time value, this would generally relate to intermittent faults, for example the condition of several trains accelerating at the same time, which leads to this current increase. However, if the time duration of the current increase is longer than the pre-set time $T$, the circuit breaker is then given the trip order. The same principle applies to the negative $I_{\text{max}-}$ value, but in this case, the trains will be regenerating.

Figures 3-2 and 3-3 illustrate the operation of the overcurrent relays.

![Figure 3-2: operation of overcurrent relays (Imax+).](image-url)
3.4 Rate-of-rise protection

When the train accelerates, there is a sudden surge in the current drawn by the train. The profile of this sharp rise of the current is similar to that of a fault in the system. Therefore, for DC supply line protection, it is difficult to distinguish between the starting currents of trains and the current produced by a remote distance fault, particularly an arcing fault. To solve this problem, many protections based on different principles have been adopted, for example the instantaneous overcurrent protection, timed overcurrent protection, and inverse time overcurrent protection, however, these protection functions seem not satisfactory. In this contest, in recent years, a new protection, known as rate-of-rise protection \((\frac{di}{dt})\), has been developed and became part of the main protections of the DC traction system.

The working principle of this protection is based on the fact that the fault currents have a higher rate-of-current-rise than the trains starting currents, and in addition the starting currents decrease very quickly after that they have reached the peak value instead the fault currents continue to rise until the fault is isolated. Therefore, this type of protection has two setting: one for \(\frac{di}{dt}\) and one for the time duration \(\Delta T\); this allows the protection to trip the corresponding circuit breaker only if the high rising rate of the feeder current persists beyond the time setting.

This protection function is usually implemented in the overcurrent relay; however, the relay must not operate for negative \(\frac{di}{dt}\) or reverse currents and hence it must be unidirectional, a feature easily obtainable with an electronic relay. Regarding the settings, they are chosen to ensure that the corresponding circuit breaker will not trip on the most severe train starting condition but will trip under distant fault condition.
As shown in figure 3-4, $\frac{di}{dt}$ protection starts when the current rising rate is higher than $\frac{di}{dt}$ setting level; if this condition continues for all the setting delay duration ($\Delta T$), the tripping is initiated.

### 3.5 Current increment protection

Also known with the name DELTA I protection ($\Delta I$), it is an extension of the rate-of-rise protection. In fact, this protection is based on the change in magnitude of the supply line current ($\Delta I$) and it is triggered by a $\frac{di}{dt}$ setting. $\Delta I$ protection starts up at the same time as the $\frac{di}{dt}$ protection, then after a set time the change in current is measured and if it exceeds the set value, determined starting from the highest train starting current, a trip is issued. The $\frac{di}{dt}$ setting can be lower than that for standard rate-of-rise protection in order to offer a better sensitivity for distant fault detection.
With figure 3-5 the working principle of the $\Delta I$ protection is well elucidated. The four waveforms represent four different situations:

1. $\frac{di}{dt}$ and $\Delta I$ are higher than the trip setting level with the increase of the step current. However, the duration ($\Delta T_1$) is less than the setting duration ($\Delta T$). Therefore, the tripping is not initiated.

2. $\Delta I$ is higher than the trip setting level and the duration is longer than the setting duration ($\Delta T$), therefore a tripping is initiated.

3. During the current rise, $\frac{di}{dt}$ for a moment goes below the setting level. However, this duration is less than the time setting of protection return ($\Delta T_{re}$), therefore, the tripping is initiated.

4. In the course of the current rises, $\frac{di}{dt}$ is reduced below the setting level with a duration of more than $\Delta T_{re}$, therefore the protection is restarted.

### 3.6 Voltage protection

Voltage fluctuations are one of the most problematic issues of all electrical power systems. If voltage starts fluctuating and reaches under or over voltage pre-set values, this can cause the damage of electrical equipment and the interruption of the service. The overhead catenary system (OCS), which supplies the electrical power to locomotives, is predisposed to tap high over-voltages (up to 12 kV). Therefore, in this contest, voltage protections are necessary to protect the feeder cables. Protection is achieved by using surge
arresters placed at the end of the overhead catenary. These devices should be nonconducting at normal working voltages, and they should become conducting when an overvoltage moderately above the working voltage occurs. The overvoltage relays associated with the surge arresters operate when its input voltage is higher than a predetermined value. The values which must be used to set the protections are defined in the European Standard 50 163 Railway applications – Supply voltages of traction systems, which has been already reported in figure 1-5.

Protection relays should be inserted to control both over and under voltages. In fact, as we have set a reference voltage for upper voltage limit, similarly we have to set up the reference lower voltage limit and the under-voltage relay is used to protect the traction system in case that the voltage drops below the set lower voltage value. Typically, this value is set at approximately $500 \, V_{dc}$ and $1000 \, V_{dc}$ for $750 \, V_{dc}$ and $1500 \, V_{dc}$ traction network respectively.

Since the traction systems are subjected to many fast under voltages which are not always due to the occurrence of faults, the under-voltage protection system needs to incorporate a time delay; this must be of the order of $100 \, ms$ and hence it renders this type of protection inadequate for close-up faults.

### 3.7 Touch voltage protection

For economic reasons, the running rails are also used as return conductor for traction currents and hence, because of the rail-to-ground and rail resistances, there will be a voltage rise between the running rail and the ground caused by the return current flows between the rails and the local ground. The voltage between the running rails and the electrical earth is also known as touch voltage. If these touch voltages exceed some defined values, they could be a danger for the passengers and the working staff; therefore, touch voltage protections must be implemented. The protection from electric shock is usually achieved by using surge arrester and voltage limiters, in fact they are used as short-circuiters between the negative and the earth. These protections are installed both in the substations and along the rail.

Voltage limiters consist of two opposite copper electrodes, insulated from each other, which produce a short-circuit by melting together, after an energy absorption beyond a specified maximum value. All the LVLs existing in the market are not reversible, once they trip they remain in short circuit condition.

These protection devices incorporate both voltage and time settings, in fact we have to remember that the acceptable touch voltages are depending on the time duration. The longer is the duration, the lower is the admissible value. The setting of the limit values of the relays will be in accordance with the Standard EN 50122-1 Railway applications – Fixed
installations - Electrical safety, earthing and the return circuit - Part 1: Protective provisions against electric shock. Maximum permissible effective touch voltages as a function of time duration has been previously shown in figure 3-2.

3.8 Auto re-close function

Line feeder breakers are also equipped with automatic reclose capability. In fact, in the event that any of the traction system protection relays take action but without an actual fault in the system, the traction power should be restored as fast as possible in order to maintain the trains in service. This automatic re-close function comes together with a line-test feature that tests out the condition of the line to see if the fault ever existed, if it has been removed or if it is still present. On receiving a confirmation from the line test device that the electrical section is healthy, the auto re-closer will then activate to re-close the DC track feeder circuit breaker. As the electrical section is normally fed by two TPSS placed on the two side of the catenary system, the line feeder circuit breaker nearest to the fault would normally be activated first. To ensure that the fault is properly cleared, the traction system incorporates an inter-tripping feature between the two breakers such that when one trips the other follows. If the fault is subsequently cleared by this action, the line test device and auto re-close action would automatically restore the power to the affected electrical section.

The auto re-close function has been introduced also for another reason in fact, the common faults in the traction system are not permanent in nature. The auto re-close function will be performed several times (usually set at three) and if the fault persists after the pre-set number of attempts, the breaker is locked out and the concerned electrical section will be kept de-energized.

3.9 Protection devices coordination and selectivity

Protection device selectivity in DC auxiliary installations is one of the most important criteria for reliable operation of substations and traction systems.

When a fault takes place in a part of the network, the faulty part should be isolated as quickly as possible, while the rest of the DC network should continue to work properly without any disturbances. This purpose can be achieved by choosing a proper setting of protection devices. In other words, the aim can be reached by implementing a good coordination (selectivity) between all the protection devices used in the network. As stated in the Standard IEC 60947-2 Low voltage equipment- Part 2: Circuit Breakers, selectivity can be obtained by coordinating appropriately the trip curves of each protection device present in the circuit.
Selectivity may be total or partial. We speak of total discrimination between two circuit breakers A and B if the maximum value of short circuit current of circuit B ($I_{scB}$) does not exceed the short-circuit trip setting of circuit-breaker A ($I_{m.A}$). Instead we have partial discrimination if the maximum short-circuit current of circuit B exceeds the short circuit trip-current setting of circuit breaker A.

Figure 3- 6: a) total discrimination, b) partial discrimination.

To understand selectivity, the concepts of “overload zone” and “short circuit zone” are introduced. With the term “overload zone” we refer to that part of the circuit breaker trip curves in which the values of the current goes from the rated current of the circuit breaker itself to 8-10 times this value. These values of current correspond to an overload situation. This condition is more frequent than a real fault. Instead with the term “short circuit zone” is indicated that part of the circuit breaker trip curves in which the values of the current are 8-10 times higher than the rated current.

Figure 3- 7: a) overload zone, b) short circuit zone.
Once the concepts of overload and short circuit zones have been explained, the different selectivity techniques and their application areas can be described.

1. **CURRENT SELECTIVITY**: this type of selectivity is based on the fact that the short circuit current will be smaller and smaller as the fault point goes downstream from the power supply to the load. Therefore, according to this observation, it is possible to isolate the damaged part of the network by setting the protections with different current values, in particular: the current setting of the downstream protective devices (on the load side) has to be lower than the current setting of the upstream protective devices (on the supply side). The most significant disadvantage of current discrimination is due to the fact that it can be applied only where there is a high impedance between the two circuit breakers concerned.

2. **TIME SELECTIVITY**: it is an evolution of the previous one. In fact, in this type of discrimination, for each protection device, a trip time is defined in addition to the tripping current value. A certain current value will make the protections trip after a defined time delay, and the values of the time delay and the tripping current increase going from downstream (load side) to upstream (supply side); but this means that the most severe faults (which are those closer to the supply) are cleared in the longest operating time.

3. **TIME-CURRENT SELECTIVITY**: in this type of coordination is used a trip characteristic according to which, as the fault current increases, the trip time of the circuit breaker decreases. Therefore, the upstream device should have a higher setting value of tripping current and a higher instantaneous trip time than the next device downstream. With time-current selectivity the two disadvantages mentioned before are overcome.

4. **ENERGY SELECTIVITY**: this technique is based on the energy dissipated in the device by the short-circuit. In the event that a high short-circuit is detected by two devices, the downstream device will significantly limit the fault current. The energy dissipated in the upstream device is not sufficient to cause it to trip: discrimination is achieved regardless of the value of the short-circuit.

5. **ZONE SELECTIVITY**: in this type of selectivity, when a short circuit current is detected, a ZSI-equipped breaker sends a signal to the upstream breaker which blocks the tripping for a specified time. If the breaker itself does not receive a blocking signal it will trip according to its settings without additional delay. This
ensures that it is always the circuit breaker closest upstream to the fault which trips and interrupts in the shortest possible time the short-circuit current. To achieve the zone discrimination the circuit breakers should be equipped with the so called “zone selective interlocking (ZSI)” function; otherwise the communication between the trip units of upstream and downstream breakers would not be possible.

In the overload zone the time-current selectivity is realized. Instead in the short circuit zone almost all the various selectivity techniques can be used; in particular, for protection against low short circuits time selectivity represents a good choice and for protection against high short circuits the best choice is energy selectivity.
4.1 Traction power substation model

Let’s model with Simulink, a toolbox of the program MATLAB, the typical scheme of a traction electrical substation feeding the dc traction system.

4.1.1 Industrial network equivalent

In the TPSS model above shown, it is possible to identify the block which represents the industrial network (A).

The MV distribution network which fed the TPSS is modelled through a three-phase voltage generator. The phase-to-phase voltage is set at 23 kV (rms) and the frequency at 50 Hz.
4.1.2 Three-winding transformer model

The industrial network is connected with the group transformer which is a three-winding transformer modelled with the following block:

The primary winding has a delta connection. Instead, as concerns the two secondary windings, one is wye connected, while the other is delta connected (Dyd11), so that on the secondary windings the voltages are displaced by 30°.

The voltage at the primary is $V_p$ and the output voltage at the secondary and tertiary windings is $V_{3,3}$. The voltage at the primary is 23 kV and the output voltage at the secondary and tertiary windings is 1.1 kV.

The equivalent circuit of a three-winding transformer is represented in figure 4-4.

![Figure 4-3: block which models a three-winding transformer.](image)

![Figure 4-4: equivalent circuit of the three-winding transformer](image)
In order to find all the parameters of the equivalent circuit of three-winding transformers, the short circuit and one open-circuit tests are done. Looking at the equivalent circuit it can be notice that to find the values of the three impedances $\bar{Z}_1, \bar{Z}_2$ and $\bar{Z}_3$, three short circuit tests must be done. In each short circuit test one winding is short-circuited, another is kept open and the last is fed with the nominal current.

From the three-short circuit tests the binary impedances $\bar{Z}_{12}, \bar{Z}_{13}$ and $\bar{Z}_{23}$ are obtained:

$$\bar{Z}_{12} = \bar{Z}_1 + \bar{Z}_2$$ (4.1)
$$\bar{Z}_{13} = \bar{Z}_1 + \bar{Z}_3$$ (4.2)
$$\bar{Z}_{23} = \bar{Z}_2 + \bar{Z}_3$$ (4.3)

From these values we can obtain the three series impedances:

$$\bar{Z}_1 = \frac{(\bar{Z}_{12} + \bar{Z}_{13} - \bar{Z}_{23})}{2}$$ (4.4)
$$\bar{Z}_2 = \frac{(\bar{Z}_{12} + \bar{Z}_{23} - \bar{Z}_{13})}{2}$$ (4.5)
$$\bar{Z}_3 = \frac{(\bar{Z}_{23} + \bar{Z}_{13} - \bar{Z}_{12})}{2}$$ (4.6)

However, the values which really matter are not the values of the series impedances, but those of short-circuit losses and the percentage values of the short-circuit voltages. These quantities can be obtained with expressions formally similar to the previous ones.

Therefore, the short-circuit losses will be:

$$p_{cc1} = \frac{(P_{12} + P_{13} - P_{23})}{2}$$ (4.7)
$$p_{cc2} = \frac{(P_{12} + P_{23} - P_{13})}{2}$$ (4.8)
$$p_{cc3} = \frac{(P_{23} + P_{13} - P_{12})}{2}$$ (4.9)

and the percentage values of the short-circuit voltages:

$$\bar{v}_{cc1} = \frac{(\bar{v}_{cc12} + \bar{v}_{cc13} - \bar{v}_{cc23})}{2}$$ (4.10)
$$\bar{v}_{cc2} = \frac{(\bar{v}_{cc12} + \bar{v}_{cc23} - \bar{v}_{cc13})}{2}$$ (4.11)
$$\bar{v}_{cc3} = \frac{(\bar{v}_{cc23} + \bar{v}_{cc13} - \bar{v}_{cc12})}{2}$$ (4.12)
Instead the open-circuit test can be performed on any one of the three windings. By performing the open circuit test, we obtain the no-load impedance in the excitation branch, no-load losses and no-load current.

### 4.1.3 Diode bridges model

To obtain the twelve-pulse rectifier the two diode bridges are connected in parallel. In parallel to each diode has been inserted a RC circuit, where the resistance has a value of 100Ω and the capacitor value is 1 μF.

![Diode Bridge Diagram](image)

*Figure 4-6 block which models the twelve-pulse rectifier.*

### 4.1.4 DC Filter

The outputs of the rectifiers are connected to some filters composed by a big reactor (6mH) in series with the positive DC busbar and some RC filters connected between the positive and negative DC busbars. The RC filters are composed by a resistance whose value is 100Ω and a capacitor of 360 μF. The filter is used to reduce the harmonics generated by the rectifiers.
4.2 Contact line and rail models

The simplest way to model the overhead contact line and the rail consist in represent them only through a resistance. As concerns the values of the two resistances the formulas to compute them have been described previously in sections 2.2 and 2.3. If for the overhead contact line, we consider a total cross section (catenary + contact wire) of 220 mm² when new and a wear coefficient of the contact line of 0.94, the resistance per unit length will result:

\[ r_c = \frac{18}{220 \cdot 0.94} \approx 0.087 \ \Omega/\text{km} \]  \hspace{1cm} (4.13)

Instead for the rail we consider a linear mass of 60 kg/m and a wear coefficient of the rail equals to 0.9, we obtain that the resistance equals:

\[ r_{rail} = \frac{0.9}{60} = 0.015 \ \Omega/\text{km} \]  \hspace{1cm} (4.14)

The sum of these the two resistances gives the total resistance of the traction circuit.

\[ r = 0.087 + 0.015 = 0.102 \ \Omega/\text{km} \]  \hspace{1cm} (4.15)

Since, in our simulation, we have to measure the rail to earth voltage along different points of the rail this modelling cannot be used. We should use the distributed parameter line model which means that the series resistance, the series inductance, the shunt conductance and the shunt capacitance are distributed along the whole length of the contact line and the rail.
As regards the contact line we will model it only with the longitudinal parameter: the series resistance, as said before, equals 0.087 $\Omega/km$ and the series inductance equals 1 $mH/km$.

![Diagram of contact line](image)

Figure 4-8: model of the contact line.

Instead, the equivalent circuit parameters of the rail, consist of a series resistance of 0.015 $\Omega/km$, an inductance of 0.66 $mH/km$ and a rail-to-earth conductance. The admissible values of the rail-to-earth conductance are reported in Standard EN 50122-2 Railway Applications - Fixed Installations - Electrical Safety, earthing and the return circuit. Part 2: Provisions against the effects of stray currents caused by DC traction systems.

<table>
<thead>
<tr>
<th>Traction System</th>
<th>Open air $S/km$</th>
<th>Tunnel $S/km$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Railway</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Mass transportation system in open formation</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Mass transportation system in closed formation</td>
<td>0.5</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4-1: recommended conductance per unit length by Standard EN 50122-2.

Stray currents and hence they corrosive effects can be reduced in two ways:

- by decreasing the series resistance of the return circuit,
- by increasing the insulation between the return circuit and the earth.

This last way corresponds to lowering as much as possible the rail-to-earth conductance, which means increasing the rail-to-earth resistance. Therefore, according to the before mentioned European Standard the rail-to-earth conductance of the running rails must be below a certain limit value; in particular, in tunnels and when the rails are new the rail-to-earth conductance cannot exceed the value of 0.5 $S/km$. Since, in our simulation, we will consider a not completely new track the shunt conductance will be a little bit higher, it will be equal to 0.83 $S/km$. This increase of the track conductance to earth is due a reduction of the
track resistance to earth; in fact, the contact between the wheels of the trains and the track produces an iron dust which decreases the insulation between the rail and the earth by decreasing the rail-to-earth resistance. Anyway, the value of the shunt conductance will be changed during the simulations, so that different situations can be analysed.

Finally, we can report the blocks which model the track in our simulation.

For a distance of 1.4 km between two consecutive substations, seven sections of 200 m have been considered.

4.3 Measuring equipment model

Upstream of the transformer, one ammeter is insert on each of the three phases in order to measure the current, which is absorbed by the TPSS. A block named “scope” is connected to each voltmeter and ammeter since it displays the signals generated during the simulation.

Instead in parallel with the train a voltmeter has been inserted to measure the voltage at the pantograph. In the following figure, the block which models the voltmeter is shown:

Other voltmeters and ammeters have been inserted in different points of the model so that the currents and the voltages necessary to the study of the problem can be measured.
4.4 Train model

In the first simulation, the train has been considered simply as a constant load which absorbs 1000 A. Therefore, it has been modelled through a current generator and through a constant whose value is -1000 A.

![Figure 4-11: first model of the train.](image)

In the final model that we will analyse, instead, the train is modelled as a variable load. Modelled the train as a variable load is a more realistic solution; in fact, in a rail system the current absorbed by the train is a function of time. To achieve this purpose the Simulink block named signal builder has been used.

Below a probable absorption diagram is reported. That diagram is only a hypothesis; however, it will allow us to make some considerations. In the diagram different parts can be distinguished: at first the acceleration phase, in which the current absorbed by the train tends to increase, is represented, then in the successive stroke the nominal power has been reached, and hence the current is constant, but the train is still accelerating. The longest stretch is associated with the phase in which the train maintains its speed, therefore the train absorbs only the energy necessary to overcome the losses resulting from its motion. Then it follows the coasting phase in which the train decelerates gradually until it reaches the braking phase.
Since in the simulation there are four trains to obtain all the absorption diagrams we have to shift in time the absorption diagram of the first train. We obtain the following situations:
Finally let's report the complete model of the train:

In parallel to the train there is a capacitor whose aim is to level the voltage at the pantograph; for these capacitors, capacities of 8 mF have been chosen. Instead, the gain equals -1000 Amps.

### 4.5 Substation grounding system model

The grounding system of the substations is constituted by a typical configuration of a ring electrode with four rods. The typical ground resistance can vary in the range from 5 to 15 Ω depending on the soil characteristics. However, the grounding system of each substation is connected to the neighbouring ones by means of the MV cables and of bare conductors. For this reason, the equivalent ground resistance that can be measured from each substation is mostly independent from the ground resistance of the single substation and from the distance between them: it has a typical value around $R_{sg} = 0.06 \, \Omega$. 
4.6 Ground fault model

Short circuit represent a class of serious faults in a power system; in fact, the short circuit current must be computed for the choice of electrical equipment and for the setting of power system protection.

In our simulation, we will analyse the ground fault along the line, since the ground fault characterises a more critical situation due to its harder detection by the protective relays. The ground fault has been modelled through an ideal switch and through a fault resistance. The ideal switch is driven by a step signal: if the step amplitude equals 0 the switch is open, and the fault is not present when the step amplitude equals 1 the switch closes and the fault begins.
The step time represents the instant in which the amplitude of the step signal passes from 0 to 1 and hence it is the instant in which the ideal switch closes, and the ground fault starts. As concerns the value of the fault resistance, it has been set initially at $R_{\text{fault}} = 0.1 \, \Omega$. During the study, we could want to analyse different fault currents, and hence the value of the fault resistance could vary.

4.7 Braking chopper model

The braking chopper is a braking unit used to control the rise of voltage when the trains feed energy back to the contact line. In particular, the braking chopper is an electrical switch that limits the DC bus voltage by switching the braking energy to a resistor where the braking
energy is converted to heat. Braking choppers are automatically activated when the actual DC bus voltage exceeds a specified level of voltage which depends on the nominal voltage of the power supply system.

In our simulation, the braking choppers are modelled through surge arresters and they are inserted in parallel with the trains. Since the nominal voltage of our traction system is $1500 \ V$, the activation voltage of the braking choppers has been set at 1900 V, so that the maximum allowable value of 1950 V is not reached.

![Diagram of surge arrester and contact line](image)

*Figure 4-20: surge arrester which models the braking chopper.*

### 4.8 Final model

In the final model, there are three electrical substations and four trains. In a subway line, the TPSSs are generally distributed in sequence in a way that the voltage drop does not exceed the 33% of the nominal value. In addition, to space the TPSSs, the landscape of the line and the environmental conditions should be considered. In our simulation, for the sake of simplicity, it has been supposed that the TPSSs are equally distributed even if, in reality, the TPSSs could not be equally spaced. The distance between two consecutive TPSSs has been set equal to 1.4 km, and hence the total length of the considered track section is assumed to be 2.8 km.
Figure 4-21: Final Simulink model.
Figure 4-22: part 1 of the final Simulink model.
Figure 4-23: part 2 of the final Simulink model.
Figure 4-24: part 3 of the final Simulink model.
5.1 Normal operation

First of all, let’s run the simulation without considering the fault and hence let’s report all the important currents and voltages waveforms under normal operating condition. The simulation time has been set at 0.7 s and the trends of currents absorbed by the four trains are the same of those reported in the previous chapter. In the following figure is reported the voltage measured across the train 1.

The voltage transient is as we expected: after an initial high peak, it oscillates around the value 1500 V remaining in the interval 1000 V ÷ 1800 V. We can notice that, after the initial peak, the second highest voltage peak occurs in the instant in which the train reaches the maximum value of supplied current in the contact line through the regenerative braking.

Figure 5-1: pantograph voltage of the train 1.
Figure 5-2 demonstrates what we have just said. In fact, train 1 reaches the maximum values of supplied current at 0.53 s and the second highest voltage peak occurs at the same time. The same observations can be done for the other trains along the track.

In the following figures are reported the currents supplied by the three TPSSs to feed the four trains.

Figure 5-3: current supplied by the TPSS 1.
Also in this case the results are as we expected; for example, the currents supplied from the first TPSS, reported in figure 5-3, and the second TPSS, reported in figure 5-4, drop to zero in the interval included between $0.5 \, \text{s}$ and $0.6 \, \text{s}$. In fact, in this interval, the train 1 is in regenerative braking and hence it supplies train 2 which is, instead, in accelerating phase. Another drop can be notice in the interval between $0.3 \, \text{s}$ and $0.4 \, \text{s}$; in fact, in this interval the train 2 is using regenerative braking therefore a lower amount of current is required to the TPSSs. The same observations can be done for the current supplied by the TPSS 3 and absorbed by train 3 and 4.

The current delivered by the TPSS 1 splits and flows in the two parallel paths, which formed the part of the circuit that we called track 1 and track 2, to supply both train 1 and train 2. Therefore, the sum of these two currents should give the current shown in figure 5-3.
which is the one supplied by TPSS 1. In addition, for future observations, it must be remembered that the currents measured by the overcurrent relays are those shown in the following figures, therefore from their values we will understand if the extra-rapid circuit breaker will trip or not.

As we can notice, the currents may assume negative values, in fact these are the currents measured at the OCS and not at the positive busbars in the substations. Clearly, when the current becomes negative, it means that the train in that track is in regenerative braking phase.
We can notice that, as expected, in normal operation condition, the voltage between the running rails and the electrical earth doesn’t exceed the value of $10 \, \text{V}$.

Finally, let’s report the currents absorbed from the industrial network by the three TPSSs.
Figure 5-9: current absorbed by - a) TPSS 1, b) TPSS 2, c) TPSS 3.
5.2 Operation under fault condition

In this paragraph, different fault conditions are analysed in order to show the most important parameters which can help in the detection of faults in DC Traction System.

5.2.1 Ground fault along the line near the substation

The first case that we are going to analyse is the case of ground fault near the substation, more specifically near TPSS 2. As already said, this case represents the worst-case as concerns the fault current, which is higher than the fault current produced by a ground fault along the line far away from the substation. In this paragraph we will prove what just said. The fault resistance has been set initially at 0.1 Ω.

First of all, let’s report the voltage across the trains.

The ground fault starts at 0.3 s; in fact, at this time, we can notice that the voltage across the train drops to a value which is around 500 V. Therefore, the protections used to detect under voltages, which are usually set about 1000 V for the traction systems which work at 1500 VDC, should notice the abnormal values and gives the alarm. The same observations can be done for the voltages across the other trains of the simulation.

Obviously, before the occurrence of the fault, the trend of these voltages is equal to that previously shown when the system was in normal operation condition, while after the drop the voltages across all the four trains set around values between 1280 and 1400V.
As expected the current supplied by the TPSSs has a sudden increase when the fault starts, since a huge amount of current is now absorbed by the fault. In particular, the increase is more marked in the TPSS near which the fault takes place; in fact, the current supplied by the TPSS 2 reaches the highest peak value of 7.80 kA with respect to the other TPSSs.

Figure 5-11: current supplied by the TPSS 1.

Figure 5-12: current supplied by the TPSS 2.
In the following figure is reported the current which flows in the fault; its value is about 10.8 kA.

A such high value of fault current is surely detected by the overcurrent protections, which open the extra-rapid circuit breakers and isolate the faulty part of the traction system.

Since the TPSS 2 is the substation closest to the fault, the current absorbed by this substation from the industrial grid has the highest increase when the fault starts. Figure 5-15 shows that the absorbed current is the double with respect to the previous case of normal operating condition.
Figure 5-15: Current absorbed by a) TPSS 1, b) TPSS 2, c) TPSS 3.
To finish, let’s see how changes the rail-to-earth voltage along the track.

![Figure 5-16: rail-to-earth voltage in one point of the track.](image)

When the fault starts the rail-to-earth voltage along all the track undergoes a sudden increase. The reason of this rapid increase can be explained by the fact that when a ground fault occurs, the fault current is injected into the ground through the fault and it flows back to the substations through the ground resistances of the rail. In this case the rail to ground voltage goes from 0 to about 200 V in approximately 20 ms; the values reached by the rail-to-ground voltage exceed the maximum allowable limit of 120 V and hence dangerous touch voltages are achieved. Anyway, the important aspect of this observation is not the final value reached, but it is to note how fast the rail-to-ground voltage increases when a ground fault occurs. In fact, as already said, the steady-state value of the rail-to-ground voltage depends on many parameters such as the rail-to-ground resistance of the track (in other words the age of the track), on the value of the fault current and hence on the value of the fault resistance. Consequently, in this case the value is 200 V, but if one of these parameters changes the steady-state value could be higher or lower and not exceed the allowable limit of 120 V.

In this last section, we proved that in case of ground fault near a substation there are many elements through which the fault condition can be noticed.

Now let’s deactivate all the models of the trains so that we can analyse how the omission of the currents absorbed and injected by trains changes the trends of the various quantity. Practically, to eliminate the influence of the trains we have to set the block “gain”, presents in all the blocks which model the trains, equal to zero. In the following, some current and voltage trends are reported to analyse the mentioned situation.
The trend of the voltage across the train remains approximately the same of that found when the current absorbed was considered, but the voltage clearly oscillate less, in fact the disturbances introduced by the trains have been eliminated. In figure 5-17 only the voltage across train 1 is reported but the same observations can be done for the voltages across the other trains.

We can say the same thing for the rail-to-earth voltage; in fact, the steady-state value remains always around 200 V and hence it continues to exceed the value allowed by the Standard EN 50122-1 (120 V), but it oscillates less if the current absorbed by the trains are not considered.
As expected the currents supplied by the TPSSs decrease since now the trains don’t absorb any current; but, apart from this, the trend doesn’t change very much, it only has less oscillations.

Therefore, as concerns the value of the current absorbed by trains, it does not affect considerably the results of the study.

\section*{5.2.2 Ground fault along the line far from the substation}

Now let’s move the ground fault far from the substation and let’s analyse the changes that occur in waveforms. In particular, the fault will be located near train 2. This is not a random choice, in fact, when the fault starts at 0.3 s, train 2 enters the regenerative phase and it represent a particularly interesting situation.

As before, first of all, we report the voltage across the trains.
After that the voltage drops at $0.1 \, \text{s}$, due to the sudden increase of the ground fault current, the voltages across train 1 reaches a steady-state value of 1000 V, instead the voltage across train 3 stabilizes around a value of 1400 V. This difference of the steady-state values is due to the different distances between the location of the fault and the trains, in fact since train 2 is the closest to the fault it will suffer the highest voltage drop.
As expected the current supplied by the TPSS 1 has the highest increase when the fault starts in fact it is the closest substation to the fault. Anyway, also the current rise of the TPSSs 2 and 3 at 0.3 s is clearly visible.

We can notice from figures 5-22 and 5-23 that the currents supplied by the TPSS 1 and TPSS 2 in the interval 0.5 ÷ 0.6 s decrease since in this interval train 1 is in regenerative braking and hence feeds train 2 which is accelerating.

More than the currents supplied by the TPSSs it is important to consider the currents seen by the protection relays. In particular, we will report the current detected by the protections at the ends of the part of the line in which the ground fault is located and then we will compare them with the set values of the over-current protections to see if the will
recognize the fault and hence trip. Before proceeding, we have to remember that for a dc traction network which works at 1500 $V_{dc}$ the most typical settings of over-current protections are in the range of $4000 \, A \, - \, 4500 \, A$.

![Figure 5-24: Current detected by the upstream overcurrent relay.](image)

![Figure 5-25: Current detected by the downstream overcurrent relay.](image)

Let’s suppose that the setting limit of the overcurrent relays is $4500 \, A$. The fault is detected by both the upstream and downstream relays and hence the high-speed circuit breakers trip, isolating the faulty part of the circuit.

From figure 5-24, we can see that the upstream protection detects the fault at 0.383 s which means after $83 \, ms$ from the moment in which the fault begins. Therefore, the high-speed dc circuit breaker will clear the fault in a time equals to $83 \, ms + T_i$, where $T_i$ is the interruption time of the circuit breaker which is usually a function of the initial rate of rise of the current.
From the above plot, we can conclude that high speed circuit breakers have a break time not greater than $30 \text{ ms}$ and it depends on the fault current initial rate of rise $\frac{dI}{dt}$.

Predictably, the fault current is lower with respect to that of the previous case in which the ground fault was located near the substation; in fact, the steady-state value is now around $8.5 \text{ kA}$.
After the occurrence of the fault, the touch voltage along the rail reaches values around 150 V, and hence the permissible value of 120 V is exceeded. This is due to the value of rail-to-earth resistance that we choose in this simulation, in fact, we are considering an almost new track in which the value of the shunt conductance is around $0.83 \, S/km$. If we consider a much older track, in which the iron dust produced by the running and by the mechanical braking of trains has reduced the isolation between the rail and the ground, in other words it has increased the shunt conductance at the value for example of $5 \, S/km$, the increase undergone by the rail-to-ground voltage will be lower and maybe it will not exceed the allowable value of 120 V. Let us prove what just said and hence let us increase the value of the running rail-to-earth conductance from $0.83 \, S/km$ to $5 \, S/km$; the touch voltage along the track is reported in figure 5-29.
By decreasing the rail-to-ground resistance of the rail, touch voltage is decreased too, and in this case, its steady-state value is about 125 V; which means lower than the previous case but still higher than the maximum allowable limit.

### 5.2.3 Undetected ground fault

In this paragraph, we will analyse the DC traction system when a ground fault occurs, and the fault current is not high enough to make the overcurrent protections trip. The value of fault currents is influenced by the following factors:

- ground fault impedance: the higher is the fault impedance the lower is the fault current;
- position of the fault: if the fault happens along the line, far away from the substation the fault current will be lower.

Therefore, to obtain an undetected ground fault, let us place the ground fault more or less in the middle point of the distance between the TPSS 1 and 2 and let us increase the fault resistance $R_{\text{fault}}$ from 0.1 Ω to 0.19 Ω. Fault resistance higher than 0.2 Ω won’t be considered since we will analyse only low impedance ground faults; anyway, it is obvious that if a high impedance ground fault had been considered, the fault currents detected would be even smaller. After applying these conditions, we can compare the detected fault current with the set value of the overcurrent protections to see if they will recognize the fault.

![Figure 5-30: current seen by the upstream overcurrent relay.](image)

The maximum value which coincides with the steady-state value is around $4.1 \, kA$. As already said this is the relay closest to the fault and hence it detects the highest fault current. If the current detected in this point doesn’t exceed the pre-set limit of the instantaneous
overcurrent protection, then no other overcurrent relay will detect the fault since the current detected will be certainly lower. Instead, regarding the slope of the current detected by the overcurrent relay, it will give an alarm since at 0.3 s, for a very short interval of time, it is higher than 500 kA/s, but this condition alone is not enough to make the extra-rapid circuit breakers trip.

The highest value of current detected by the downstream relay is 3.7 kA and hence the instantaneous overcurrent protection doesn’t detect the fault. Also in this case the $di/dt$ protection gives an alarm, since the $di/dt$ setting value, for a very small time at 0.3 s is exceeded; but, again, only this condition cannot order the trip of the extra-rapid. Therefore, we can conclude that no protection recognizes the fault which, hence, remains undetected.

The fault current passes from 8.5 kA to 5.8 kA, since the position of the fault remains the same with respect to the previous case, this reduction is only due to the increase of the fault resistance which has been increased from 0.1 Ω to 0.19 Ω.
The fault is not detected by the protections, but it exists and hence at 0.3 s when it occurs the TPSSs absorbs and supplies more current with respect to the normal operation.

Finally let’s analyse the voltages which last between the running rail and the earth.
By considering the steady-state values of the measured rail-to-earth voltages we can notice that the touch voltages measured in the part of the track between the TPSSs 1 and 2 are higher than the touch voltages measured in the track between TPSSs 2 and 3; therefore, we can conclude that the closer is the point to the fault the higher will be the touch voltage measured in that point. In this last examined case, the touch voltage doesn’t exceed the permissible limit of 120 V in any point of the track but, in any case, it has an abrupt increase when the fault starts. The fact that the touch voltage remains lower than 120 V is due to many factors, in fact, if the insulation between the running rail and the earth increases, the touch voltages increase too while the fault current remains almost the same; another solution to see a higher touch voltage is to decrease the fault resistance so that the fault current
increase and hence the voltage between the rails and the earth increases too; but with this approach the fault current could exceed the set limit of the overcurrent protections and hence be detected.

5.2.4 Effects of the current absorbed by the vehicles

In this section, we are going to analyse the effects of the currents absorbed by the trains on the severity of the fault.

As first case, let us consider the situation in which all the trains are deactivated and let us report the figures and the measures taken on the fault current, the current seen by the overcurrent protection nearest to the fault and on the touch voltage in a point of the track near the fault point.

![Figure 5-37: fault current without the influence of trains.](image)

If we compare the above fault current with the fault current of the previous case, shown in figure 5-32, we can notice that if we eliminate the influence of the trains the steady-state value of the fault current undergoes a slight increase. A possible explanation to this phenomenon may reside in the fact that without the trains, which absorbs a part of the current supplied by the TPSSs, all the current is now absorbed by the fault. This fact could represent a disadvantage since a higher fault current damages the equipment faster. Anyway, in our simulation the increase is very small (about 200 A) and hence quite irrelevant.

Let us now analyse the variations undergone by the current detected by the protection closest to the fault. In particular we will consider the variation in the initial rate of rise of the current and in the maximum reached value. The slope of the current detected by the
protection has been computed through the derivate instead the maximum values have been found with the tool “Peak Finder”.

![Figure 5-38: current detected by the nearest protection without the influence of the trains.](image)

![Figure 5-39: comparison of the current slope.](image)

From figure 5-39 we can notice that the slope of the fault current detected by the protection is higher if the trains are not considered, but also in this case the variation is not significant. Instead the difference between the maximum values is more important. Without consider the trains, the maximum value of the current detected by the nearest protection is about 3,25 kA while if the trains are taken into account the maximum value reaches 4,1 kA which is closer to the pre-set tripping limit of 4,5 kA. This observation leads to an inevitable conclusion: when the trains are not considered, the protections see only the current absorbed by the fault and even if this current is increased slightly the increase cannot be high enough to replace the sum of the currents absorbed by the trains during their run and hence this is the reason why the current detected by protections decreases if the trains are disabled.
As concerns the touch voltage, it doesn’t undergo any changes and it remains near the value found in the previous case which is about 110 V.

### 5.2.5 Effects of the regenerative braking

In this paragraph we are going to see what happens if the train which runs near the ground fault doesn’t use the regenerative braking. In practice, this condition is obtained in our simulation by substituting the current characteristic of train 2 with that of train 3, in which the regenerative braking occurs between 0.1÷0.2 s and hence before the fault begins.

Also in this case the fault current doesn’t change meaningfully, in fact its steady-state value is around 5.9 kA.
From this last figure, we can notice that the maximum reached value of the current detected by the protection nearest the fault is 4.4 kA and hence the current detected is now much closer to the set limit of the extra-rapid circuit breaker.

Therefore, we can conclude that the presence of a train in regenerative braking near the fault will be a disadvantage as regards the detection of the fault, in fact the current reintroduced in the DC feeder by the regenerative braking will go to feed the fault and hence will lead to an increase of the fault current without the protections noticing anything, in other words the presence of a train in regenerative braking phase near the fault increase the severity of the fault without increasing the probability that the protections recognize the fault.

### 5.3 Automatic grounding system

Automatic negative rail grounding devices continuously monitor the return rail-to-ground voltage and if the device detects dangerous voltage conditions, it connects the running rails to the ground in a timely, effective and safe manner. As concerns the setting of these devices we know that according to the Standard EN 50122-1, the maximum permissible effective touch voltage is 120V, but the setting limits are obviously lower than 120 V to keep a safety margin and they can be very different passing from settings of 50 V to settings of 110 V; after some simulations, in our model, we will set the trip of these protections at 90 V. Automatic grounding devices are usually located in electrical substations, passenger stations and in other accessible locations.

In our model, these devices have been represented through the block represented in figure 5-43 and they have been placed at the beginning of the tracks, near the substations.
5.3.1 Automatic grounding system in case of undetected ground fault

Let’s analyse the changes introduce by the operation of the automatic grounding devices in case of undetected ground fault.

From figures 5-35 and 5-36 we can notice that, when the fault occurs, the touch voltages is very close to the maximum allowable value of 120 V in all the track considered; instead in this case, thanks to the action of automatic grounding devices, the running rail-to-earth voltage is reduced, and hence the probability of achieving dangerous touch voltages have been decreased.
It is particularly important to note that only the grounding devices located near the TPSS 1 and TPSS 2 trip, in fact, after their operation the rail-to-earth voltage along the part of the track between TPSS 2 and TPSS 3 is not high enough to make the grounding device of TPSS 3 snap.

Now let’s see how the trip of the grounding devices changes the situation in terms of fault current.
The fault current increases with respect to the case without grounding devices, its steady-state value passes from 5.8 kA to 6.1 kA and the highest peak passes from 7.5 kA to 7.9 kA. Since the fault current is increased, obviously the current detected by the protections increase too and the probability that the protections recognize the fault is greater; in fact, as we can notice from figure 5-47, now the protection closest to the fault measures a maximum value of 4.38 kA.

When the automatic grounding devices trip, the resistance of the grounding device (which is very low) becomes in parallel with the rail-to-earth resistance of the rail and hence the equivalent resistance seen from the fault point decreases accordingly. This justify why the...
fault current is increased with respect to the case in which the grounding devices were not activated. In particular, the newer is the track the more marked is this increase of the equivalent rail-to-earth resistance seen from the fault. Anyway, as in this case, this increase is not always high enough to make the high-speed circuit breaker snap.

After this last analysis, we can conclude that, even if the installation of automatic grounding devices improves the safety of the system, it is not completely sufficient since the increase of the fault current caused by the action of these devices could not be enough to make the extra-rapid DC circuit breakers trip. Therefore, these devices are used only as protection against the rise of dangerous touch voltages.
CHAPTER 6
NEW PROTECTION SCHEME

In the previous chapter we ascertain that the detection of ground faults represents a problematic issue in DC traction systems. The devices used to detect and locate the faults are overcurrent relays and current rising rate \( (\frac{di}{dt}) \) relays instead the over-voltages which rise between the rail and the ground or between the positive and the negative conductors are monitored by the over and under-voltage protections. Anyway, as previously demonstrated, if all these protections are used separately they could not be sufficient to detect all the ground faults, in particular they may fail when the fault occurs far from the substation, in fact in this situation the fault current detected by the overcurrent relays assumes its lowest value and becomes comparable with overload currents.

6.1 Trigger conditions

In this chapter we are going to implement and analyse a new protection scheme, whose purpose is to be more reliable and to detect also the most distant fault condition. The news introduced in this scheme derive from all the conclusions found in the previous simulations; in fact, we proved that if the fault is far from the substations the current detected by the relays doesn’t reach the set value of 4500 A and hence the fault remains undetected causing very serious issues to all the equipment. Instead in par. 5.3 we proved that if a line-to-ground fault is present the rail-to-ground voltage undergoes a high surge and, in particular, the closer is the fault to the point in which the voltage is measured the higher will be the increase measured. By putting together these observations, we arrived to define the new proposed scheme in which the voltage protections have been connected with the overcurrent protections.
In the new protection scheme, the circuit breaker will receive the tripping order if one of the following conditions is satisfied:

1. The current measured from the instantaneous overcurrent protection is higher than 4500 A.

2. The current measured from the overcurrent relay is higher than 4000 A and the rail-to-ground voltage is higher than 90 V (in other words the automatic grounding device closest to that protection is tripped). This condition is particularly important for the detection of the ground faults; in fact, when this type of fault takes place in the traction system the fault current injected in the ground return to the substations through the shunt resistance of the rail, this leads to a dangerous increase of the rail-to-voltage which becomes a sort of alarm for the ground faults.

3. The current measured from the overcurrent relay is higher than 4000 A and the slope of the same current reaches values higher than 500 kA/s. This third condition becomes significant when in the system are present short-circuits, in fact, in this case the rail-to-ground voltage doesn’t arise considerably and hence the second condition cannot be satisfied.

From these conditions we can notice that if the actions of the protections are combined the limits can be set with lower values.

### 6.2 Simulink model

The new scheme has been developed in Simulink through the model reported in figure 6.1. The inputs 1,2 and 3 represent the current measured by the overcurrent relay, instead the input 4 represent the state of the automatic grounding device located near the substation closest to the overcurrent relay. The transfer function \( \frac{s}{0.0015s+1} \) is used to compute the derivative of the current measured by the overcurrent relay, in other words it represents the \( \frac{di}{dt} \) protection. The output of this system is connected with the Simulink block “ideal switch”, which represents a high-speed circuit breaker.

The trip conditions are expressed in the following way “\((u_3) \mid (u_1 \& u_4) \mid (u_2 \& u_1)\)” inside the IF block. Obviously, if one of these conditions is verified the ideal switch receives the trip order.
Figure 6-1: New protection scheme Simulink model.
6.3 Analysis and simulation in case of ground fault

The traction system is in the condition of undetected fault described in par. 5.2.3, but now the new protection scheme is introduced in the Simulink model. In particular, we want to find out if these new protections allow the detection of the fault, which remains, instead, undetected with the standard protection scheme. In the following we will report the currents and voltages trends from which it is possible to understand if the desired results have been achieved.

The fault starts at 0.3 s, therefore, from this instant of time a large amount of current is injected into the ground and then it passes through the ground resistances of the running rail to return in the substations. Since the TPSS 1 is the closest substation to the fault, the touch voltage near this substation rises faster and higher than in the other substations along the track; when this voltage reaches 90 V, the automatic grounding device snaps and the running rail is directly connected to the ground.

![Figure 6-2: rail-to-ground voltage near TPSS 1.](image-url)
As regards the rail-to-ground voltage near the TPSS 2, we can do the same observations, in fact the automatic grounding device located in TPSS 2 trips too.

Now let’s apply the new protection scheme and let’s analyse the current detected by the overcurrent relays placed at the ends of the part of the track in which the fault takes place.

When the fault starts, the current supplied by substations 1 and 2 increases, as now the substations must supply also the fault, and not only the trains. Obviously, this increase is detected by the overcurrent relays located at the ends of the faulty section of the traction system; in particular, the highest increase is detected in the overcurrent relay closest to the fault. Looking the figure 6-4, we can notice that at 0.3 s the current detected increases rapidly.
with a maximum slope of 475 kA/s. About 0.2 s after the occurrence of the fault, precisely at 0.509 s, the current detected by the upstream relay reaches 4000 A. This means that from this moment the condition, according to which the circuit breaker trip if the current measured from the overcurrent relay is higher than 4000 A and the rail-to-ground voltage is higher than 90 V, is verified and hence the trip order is given to the high-speed circuit breaker. The action of the circuit breaker is clearly represented in figure 6-4, in fact, at about 0.5 s the current measured by the upstream protection is 0 and it remains 0 until the end of the simulation.

When the upstream extra-rapid circuit breaker opens, the TPSS 1 no longer supplies the fault, this means that, starting from this moment on, the fault is supplied by the substations 2. Therefore, the current measured by the downstream protection undergoes an extremely rapid increase and it quickly achieves 4000 A. From this moment, also for this protection, the condition according to which the current measured must be higher than 4000 A and, at the same time, the rail-to-ground voltage higher than 90 V is satisfied and hence the trip order is given to the downstream extra-rapid circuit breaker. All the last described passages happen very fast, in almost 2 ms, in fact the trip order is given at the downstream extra-rapid at 0.511 s.

![Figure 6-5: current detected by the downstream overcurrent relay.](image)

Therefore, we can conclude that with this new protection scheme the fault is recognized; in particular, it is detected and isolated in almost 0.2 s.

It is particularly important to note that no other circuit breaker, apart from those at the ends of the faulty section, opens; this means that this protection scheme allows the detection of the fault, but it doesn’t cause unwanted openings.
6.4 Analysis and simulation in case of short circuit

The detection of the short circuits is not so difficult as the detection of ground faults, in fact the short circuit causes a large fault current to flow in the damaged part of the system; therefore, the set limit of the instantaneous overcurrent protections is almost always reached. Anyway, to demonstrate the efficiency and the reliability of the new protection scheme also this situation has been analysed.

Let’s suppose that the short circuit takes place in the same position of the previous ground fault. The short circuit current is about \(23 \, kA\).

\[
\begin{align*}
\text{Figure 6-6: short circuit current.}
\end{align*}
\]

Even if the short circuit current is much higher than the ground fault current, now the rail-to-ground voltage doesn’t undergo the high increase that it suffered in case of fault ground, in fact, in case of short circuit, the fault current returns to the substation through the rails therefore a large amount of fault current no longer pass through the shunt resistances.
From figure 6-7, we can conclude that the automatic grounding devices don’t trip since the touch voltage doesn’t exceed the set limit of 90 V.

As we can notice from figure 6-8, the short circuit would be detected by the overcurrent instantaneous protection at 0.316 s, when the measured current reaches 4500 A.

Let’s now apply the new protection scheme and let’s analyse its behaviour with this type of fault. Obviously, the condition, according to which the trip order is given if the current measured from the overcurrent relay is higher than 4000 A and the rail-to-ground voltage is higher than 60 V, cannot be satisfied since, as previously said, with this type of fault the rail-
to-ground voltage doesn’t experience a high increase as in case of ground fault. Therefore, the high-speed circuit breakers open only if one of the other two conditions is verified.

![Figure 6-9: current detected by the upstream overcurrent relay.](image)

The rate-of-rise of the short circuit current is about $810 \, \text{kA/s}$, therefore it is much higher than the rate-of-rise of the starting current, which instead is about $300 \, \text{kA/s}$.

From figures 6-9 and 6-10, we can conclude that the high-speed circuit breaker, controlled by the overcurrent relay located upstream of the short circuit, opens at $0.314 \, \text{s}$ thanks to the condition according to which the current detected must be higher than $4000 \, \text{A}$ and the slope of the same current higher than $500 \, \text{kA/s}$.

![Figure 6-10: current slope detected by the di/dt protection.](image)
As we expect, when the upstream circuit breaker opens, the downstream extra-rapid opens too after a very short time, since the associated overcurrent relay detects a very high current due to the fact that the short circuit is now supplies by the TPSS 2.

The order trip to the downstream high-speed circuit breaker is given because it is satisfied the condition according to which the \( \frac{di}{dt} \) must be higher than 500 \( kA/s \) and the current must be higher than 4000 \( A \).

After all the observations done, we can conclude that this new protection scheme is not only useful for the detection and isolation of ground faults but it give benefits also in case of short circuits, since it makes the detection of this type of fault faster; in fact, even if the short
circuits would certainly have been noticed by the overcurrent instantaneous protection, with
the application of this new protection scheme they are detected and isolated in a shorter
time, as the short circuit currents satisfy the condition $di/dt > 500 \, kA/s$ & $i > 4000 \, A$ before
that the condition $i > 4500 \, A$ is verified.

6.5 Setting of the limits of the trigger conditions

In this last chapter a new protection scheme has been presented and analysed. In
particular, we saw that this protection scheme bases its working principle on three trigger
conditions: the extra-rapid circuit breakers open if:

1. $i > i_{\text{set1}}$
2. $v_{\text{rail-to-ground}} > v_{\text{set}}$ & $i > i_{\text{set2}}$
3. $\frac{di}{dt} > \frac{di}{dt}_{\text{set}}$ & $i > i_{\text{set2}}$

Obviously, $i_{\text{set1}}$ is higher than $i_{\text{set2}}$, otherwise the conditions 2 and 3 would be useless.

In the protection scheme applied to our model, all the limits have been set according to the
results obtained in the previous simulations, since for these types of protections no standards
have been pronounced.

In this paragraph we are going to explain why the used set values have been chosen and
which factors influence them.

Let’s start with the maximum instantaneous overcurrent protection. Its limit has been
set in our simulation at 4500 $A$. This is a typical set value in traction systems with a DC rated
voltage of 1500 $V_{cc}$, in particular the trigger limit of the instantaneous overcurrent protection
of these systems is almost always contained in the interval of values which goes from
3500 ÷ 5000 $A$. Instead, for traction systems fed with a DC rated voltage of 750 $A$ the set
value is limited in the interval 7000 ÷ 8500 $A$ and for the railway system with a DC rated
voltage of 3 $kV_{cc}$ the set limit is included in the interval 1500 ÷ 3000 $A$.

As already said, even if the set values have been obtained experimentally they find a
justification in the equivalent model of the fault. Let’s assume that a short circuit occurs
between two consecutive TPSSs, but not a short circuit between the contact line and the rails,
let’s consider instead a fault to a pole along the line; in fact, this type of fault turns into a
short circuit when the running rail is connected to the grounding system of the support, and
in addition this type of short circuit is the worst case with regard to the setting of the
protections since it takes into account the resistance between the rail and the support. The
equivalent circuit of the described situation is represented in figure 6-13. The extra-rapid
circuit breakers are called J1 and J2. The distance between the two substations is unknown
and equal to L, the two TPSSs supply a nominal voltage $V_n$, $R$ is the resistance between the
support and the rail, $\eta_i$ is the internal equivalent resistance of the TPSS, the rail and contact line resistances for km are respectively $\rho_{cl}$ and $\rho_{rail}$.

![Diagram of equivalent circuit of short circuit between two TPSS.](image)

**Figure 6-13: equivalent circuit of short circuit between two TPSS.**

The worst position of the short circuit as concerns the calibration of the protections is when it takes place in the middle point between the two substations. Therefore, let’s consider $x = L/2$. The set value of the instantaneous overcurrent protection can be estimated through the following formula:

$$i_{set1} \approx \frac{V_n}{r_i + R + \rho_{cl} \left(\frac{L}{2}\right) + \rho_{rail} \left(\frac{L}{2}\right)}$$  \hspace{1cm} (6.1)

Once that the setting of the instantaneous overcurrent protection has been done, the set value $i_{set2}$ can be easily find. In fact, the value of $i_{set2}$ must be necessarily lower than the value of $i_{set1}$, otherwise the conditions implemented in the new protection scheme become pointless. In our model we choose for $i_{set2}$ a value 500 A lower than the value of $i_{set1}$, which means that we set $i_{set2} = 4000$ A; looking at the results of the simulations the value chosen for $i_{set2}$ seems to represent a good choice. We could have chosen an even lower value, with this choice the extra-rapid circuit breakers will open earlier, and they would have isolated the fault in a shorter time, anyway a too low set value could lead to some unwanted openings. In particular, looking at the results of our simulation, we can conclude that a good set value for $i_{set2}$, can be found in the interval:

$$i_{set1} - 1000 \text{ A} \leq i_{set2} \leq i_{set1} - 500 \text{ A}$$  \hspace{1cm} (6.2)

As regard the set value of the automatic grounding device, in part, we have an advantage with respect to the other set limits, since we can exploit the Standard EN 50122-1, according to which the maximum permissible touch voltage, which can last for an indefinite time, is 120V; obviously, the automatic grounding devices are set taking into account a safety
margin, which can lower the set limit to a value of 50 V. Usually the set value chosen for these devices is limited in the interval:

$$50 \, V \leq v_{set} \leq 100 \, V$$  \hspace{1cm} (6.3)$$

A set value lower than 50 V must be avoided because it could cause the trip of the automatic grounding devices also in normal operation condition, instead a higher set value than 100 V must be avoided because it would not consider a proper safe margin from the maximum allowable value. In our model, after few simulations, we choose a $v_{set}$ equals 90 V since it well adapts with the value considered for the shunt conductance of the rail (0.83 S/km).

Really, the optimal solution for the set of these devices would be that according to which the trigger value changes as the shunt conductance varies significantly. In fact, the shunt conductance increases with the aging of the rail and if the shunt conductance increases (which means that the rail-to-ground resistance decreases), the measured rail-to-ground voltage decreases. Therefore, if the grounding device has been set with a certain value, over time, this value could be no longer reached; this means that in case of ground fault the automatic grounding devices will not trip and hence the corresponding condition of the new protection scheme will become useless.

Figure 6-14: rail-to-ground voltage with a shunt conductance of the rail equal to 0.5 S/km.
In the above figures is shown the rail-to-ground voltage measured by the same automatic grounding device, which is the one located in the substation closest to the fault point, in case of ground fault; the ground fault considered has always the same position and the fault resistance remains equal too. In figure 6-14 a new track has been considered, in fact the shunt conductance is equal to $0.5 \, \text{S/} \text{km}$; instead in figure 6-15 has been considered the same track, but years later, when the shunt conductance is increased and maybe it has reached the value of $10 \, \text{S/} \text{km}$ and hence the track results no longer well isolated from the earth. As expected, the measured rail-to-ground voltage is higher in figure 6-14, therefore if the trigger value of the automatic grounding device has been set at $3 \, \text{V}$, the device trips only in the first case, which means as long as the track is more or less new, instead, over time, the condition will be no longer satisfied and hence, to not make these devices useless, the set value should be lower for example at $60 \, \text{V}$.

Finally, the last set value to discuss is that concerning the limit to apply to the rate-of-rise of the measured current ($\frac{dI}{dt} |_{\text{set}}$). Also in this case the limit has been set according to experimental data since no standard has been pronounced about this value. After the simulations of various fault and normal operating conditions, it has been concluded that a good set value for $\frac{dI}{dt} |_{\text{set}}$ would be $500 \, \text{kA/s}$. In fact, as can be noticed from the results reported in the following figures, this value is higher than the rate-of-rise of the starting current, which in our model is around $300 \, \text{kA/s}$, but anyway it is low enough to detect the short-circuits and also some ground faults which don’t occur too far from the substations.
Figure 6-16: Rate-of-current rise in normal operating condition.

Figure 6-17: Rate-of-current rise in case of ground fault.

Figure 6-18: Rate-of-current rise in case of short-circuit.
Obviously, the chosen value works well in our model, where the distance between two adjacent TPSSs has been put equal to 1.4 km. If this distance had been chosen much higher, it is clear that the current transient would be much slower and hence the value 500 kA/s would be too high. Anyway, since in this model a subway system has been considered and analysed, the chosen value for the distance between two consecutive TPSSs and hence that chosen as set limit for the current slope are reliable.
CONCLUSIONS

The aim of this work was the implementation of a new protection scheme, to be used to protect the DC feeder of DC Traction Systems; in particular to protect those systems which widely exploit the regenerative braking.

The first chapter focuses on the regenerative braking. The growing interest shown in this kind of technology is justified by the positive effects that it has on the traction systems. In fact, the electric braking, reducing the energy consumption of the vehicles and extending the life of the braking system, improves the energy efficiency of the system. Anyway, some problems bring by this technology, such as over-voltages, have been analysed too.

The second chapter and the third give a general idea on the supply of the traction system and on the protection devices used to protect it. They treat the features and the characteristics of all the parts (starting from the HV primary lines arriving to the ground circuit) which form the traction system and ensure its proper functioning.

After that, in the second part of this work the Simulink model of a part of a subway system, fed by three TPSSs 1.4 km apart and with a DC rated voltage of 1500 $V_{DC}$, has been implemented and analysed. Different fault conditions have been simulated, in particular the fault has remained a ground fault, but some parameters of the model have been changed during the simulations in order to test their influence on the detection of the fault. Starting from the first obtained results we can conclude that a ground fault along the line and far from the TPSS represents the most severe condition as concerns the detection of the fault, since a fault near the TPSS produces a higher fault current, and hence it is easier to detect for the protections. Then, in the subsequent series of simulations, the fault resistance has been increased so that we were able to study a fault condition in which the current measured by the overcurrent protections didn’t exceed the set value, the circuit breakers didn’t receive the trip order and hence the fault remained undetected. Once this condition has been achieved, the results of the simulations prove that:

1. If a train is in regenerative braking near the fault, it makes the detection of the fault more difficult, since the current that comes from the recover energy goes to supply the fault without the protections suspecting anything.
2. In case of ground fault, the rail-to-ground voltage, in particular near the fault point, undergoes a high sudden rise.
3. The rate-of-rise of the fault current is higher than the rate-of-rise of the starting current. The difference is more visible in case of short-circuit, in fact this type of fault causes the highest current rate of rise ($di/dt$).
By combining all these observations, in the last chapter, a new protection scheme for the DC feeder has been built and tested in both the conditions of ground fault and short-circuit. Finally, from the results of the tests, it was possible to conclude that the new proposed solution well works in different fault conditions and all the problems coming from the standard protections, with the exploitation of this protection scheme, are overcome and solved.
References


