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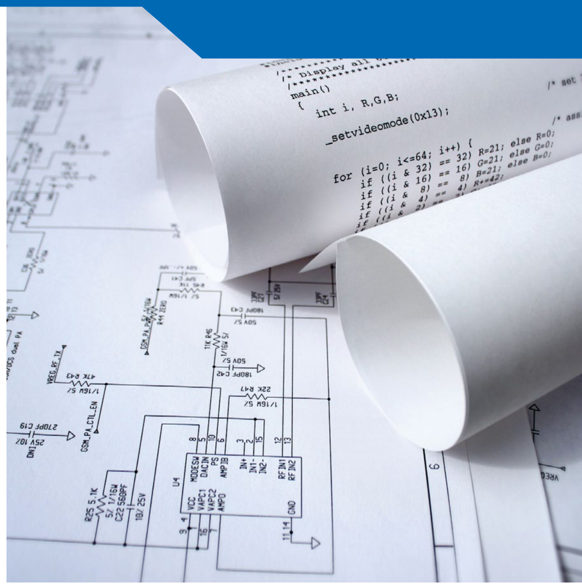
WHITEPAPER

DC railways applications

Voltage Limiting Devices



Reasons and effects of stray currents

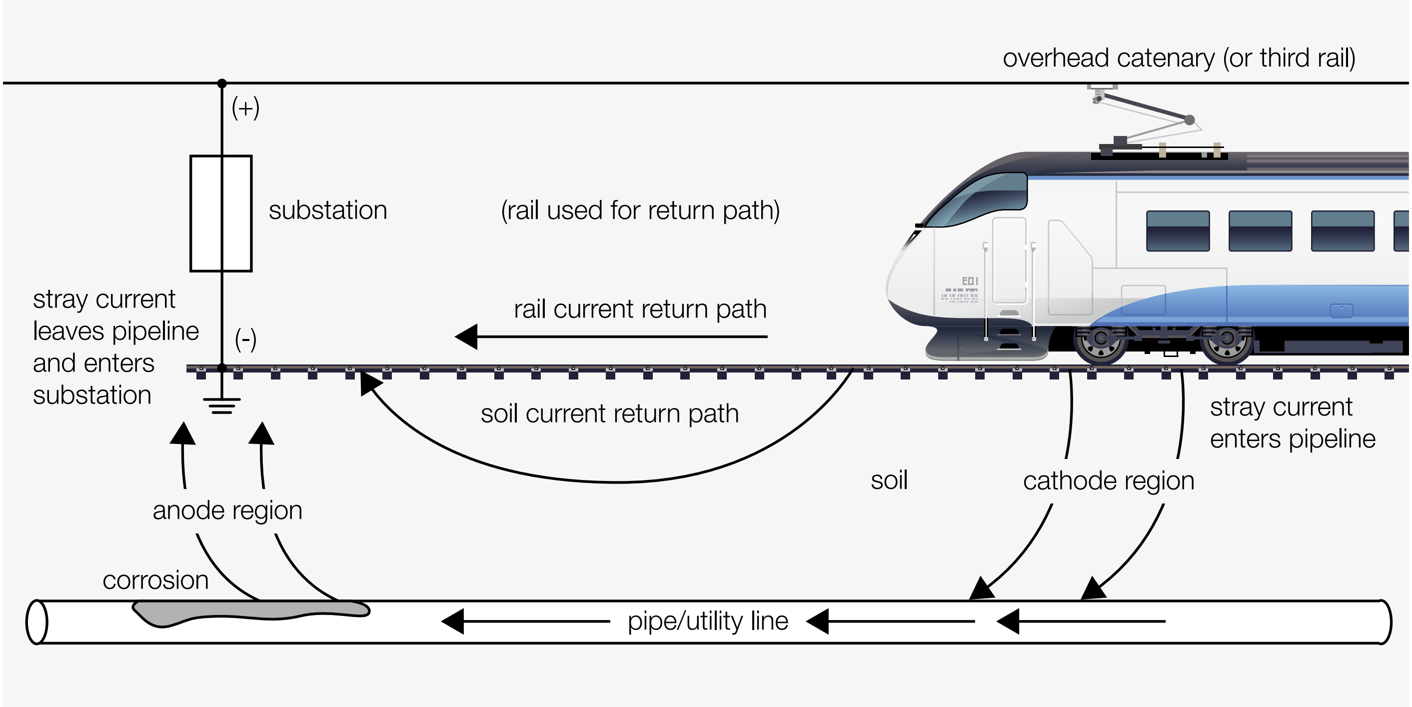
Electric railways are using rails as a robust electrical conductor for return currents from the trainsets back to the power supply substations. As the electrical conductivity of even a massive rail is limited (i.e. the rails feature a specific value of electrical resistance and inductance), and the rails cannot be perfectly isolated from the earth (in addition to regular leakage currents arising in the track via limited impedance of track isolation a significant occurrence of current leakage can be observed e.g. at places with contaminated ballast, railroad crossings etc.), a part of the return current, also known as stray current, escapes from the rails to the environment and flows outside of the rails through parallel paths with the lowest resistance, i.e. through the surrounding soil and, in particular, nearby conductive structures back to traction power substations, in accordance with the principles of Ohm´s and Kirchhoff´s circuit laws.

The conductive structures are mostly steel constructions or reinforcements embedded in iron-concrete buildings along the railroad (bridges, tunnels, …), pipelines, metallic cables of railway signalling systems, telecommunication cables, etc. Alternating currents do not imply a risk for the above structures, but the more dangerous is the long-term influence of direct currents. In principle it is an electrochemical reaction similar to the zinc electroplating (galvanization) process in which metallic material from zinc anode is transferred to a zinc-plated object (cathode) by the interaction of direct current, and causing the volume of zinc anode to decrease. Similarly, the stray DC currents cause corrosion at the anode area of the conductive component (i.e. at area where the stray current leaves the steel structure lying in parallel with the railway), causing loss of the metallic material there.

Long-term exposure of these even small currents may result in material losses which later on destroy the affected structure. Concerning the rate of decrease of the material we may use the Faraday law. Let us consider an average traction current of 1000 A and the share of stray currents of 0.1 per cent (i.e. 1A). Over the period of one year this stray current is able to transfer up to 9 kg of iron or over the double amount of copper. Since the stray currents may attain the multiple of the value considered, the related risks may play a very important role.

In case of reinforced concrete structures the corrosion process is linked with local expansion of the corroded reinforcement, causing cracks in the iron-concrete blocks due to the resulting pressure and thus loss of stiffness and load-bearing capacity. In a better case that means periodical inspections to the infrastructures affected, related with costly repairs, i.e. a very high OPEX (OPerating EXpenses) and CAPEX (i.e. CAPital EXpenses), and, in extreme cases a fatal crash with major damage both to the property and sometimes to human life.

Fig. 1 DC stray currents and their effect on steel structures, resulting from earthed or improperly insulated rails.



Safety of persons and animals first

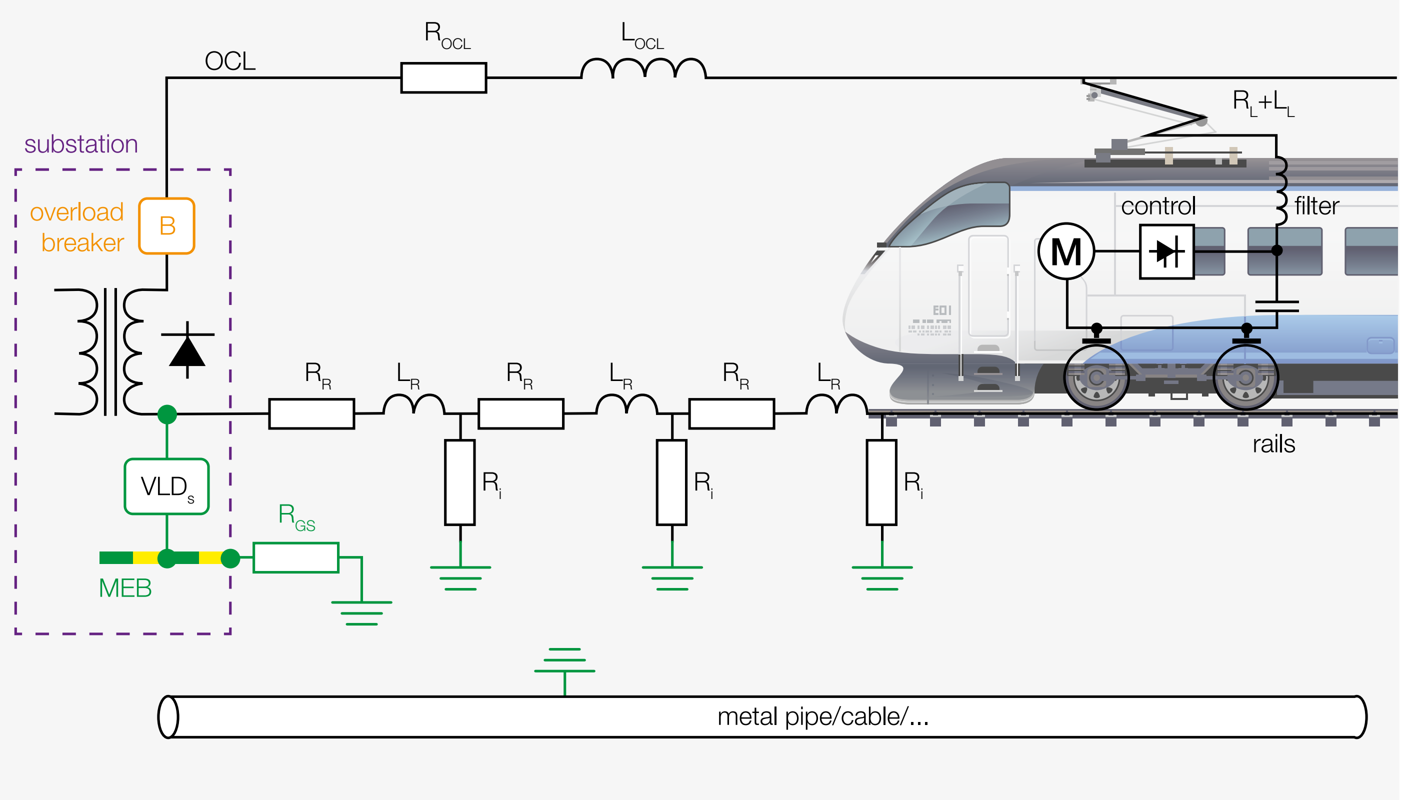
Most DC powered electrical railways worldwide (tramways, underground railroads, DC railways) are using return circuit (rails) insulated from the earthing system. A simplified diagram of such a system is shown in Fig. 2, where R_i represents the quality of insulation between the rail and the surrounding soil, R_{GS} is the quality of earthing of the power supply substation, and the series combination $R_{OCL} + L_{OCL} + \Sigma(R_R + L_R)$ is the total impedance of the electric traction loop (overhead contact line and the rails at the track section considered). The impedance of the locomotive (engine) (R_L+L_L) can mostly be neglected.

The objective of this engineering approach is to limit to the extent possible the leakage of stray currents into the railway vicinity where metallic structures can often be found (in particular in urban areas), which might suffer a fatal damage by long-term exposure to even a relatively small DC stray currents. The achievement of high values of Ri means that the track superstructures must be designed and realized at appropriate quality level, but also be maintained accordingly, because dirt in the ballast and damage to the insulated fixing elements etc. may after a while significantly deteriorate the Ri impedance value and, consequently, result in increased corrosion due to stray currents.

This concept of insulated rails , however, features one significant negative aspect. The operation of railway systems with floating return conductor (rails) causes voltage drops to arise on the return conductor due to the return conductor´s impedance $\Sigma(R_R + L_R)$. In some circumstances the voltage arising on insulated rails against the ground may achieve relatively high values and be life-threatening for living organisms in the railway vicinity (passengers, railway personnel, farm and wild animals, etc.).

The occurrence of such dangerous voltages may also be caused by long railway section between the substations, by higher number of trainsets running within the commonly powered railway section, by the operation of trainsets with regenerative braking, slowly reacting disconnectors at the traction substations, and in some cases also by the inability of substation disconnectors to distinguish the fault (short-circuit) current from the operating electric current, which is true in particular for short circuits arising at a greater distance from the power substation (e.g. the OCL fallen on the rail, or short-circuit in the locomotive) in which case the total impedance causes the short-circuit current to be limited to values similar to operating current ranges. Similar situations may arise at the moment when the ground resistance of the earthing system of the MEB of the traction substation becomes deteriorated (increased), or the OCL falling down outside the rails on earthed parts of the railway infrastructure. In such a case the higher resistance of the impedance loop could cause the fault currents to be decreased below the tripping values of the disconnectors.

Fig. 2 Simplified model of insulated DC railway traction.



From the above examples it results that dangerous touch voltages along the railroad may arise not only during the occurrence of the failure, but also during the normal operation on the track. All these risks have to be treated using a voltage limiting device (VLD). The highest permissible voltage values against the ground (i.e. against earthed, electrically conductive structures installed around the railway) as a function of time are defined by EN 50122-1 standard. The railway operator is obliged to make sure that those limits are not exceeded at any point of the track. The most commonly used limit values at any place of the railway are 120 V DC, and 60 V DC at railway workshops (some national regulations may specify lower values). It is usually difficult to predict the occurrence of this unwanted voltage peaks, in particular in modern railways, where, in addition to normal parameters , the occurrence is being influenced by the impedance of the overhead contact line and the return circuit, the power consumption of the trainsets, their density and location along the railway line, the regenerative braking system, modern machinery driven by AC motors with IGBT DC/AC inverters, etc.

Not exceeding of these limits can be ensured by a number of ways – e.g. by reducing the length of the traction circuit, thus by increasing the number of power supply substations, which results in decreasing of the series impedance of the respective traction circuit, by decreasing the series impedances of the electrical power supply circuit (e.g. by increasing the electrical conductivity of the rails or by an auxiliary return conductor installed in parallel), etc. These measures, however, conflict with the need for significant investment increase, and other complications. In such instances voltage limiting devices (VLDs) may be helpful and efficient solution for the removal of risks. By balancing of all the above solutions, a functional and safe traction system and optimized CAPEX and OPEX may be achieved.

SALTEK voltage limiting devices used in DC powered railway lines

The voltage limiting devices (referred to as VLD, OVPD, RPCD, etc.) are designed to meet two conflicting requirements at significant points of the electric railway lines:

1. Ensure the safety of persons, animals and often some important technology against the effects of excessive voltages arising between the insulated rail and the surroundings by connecting the rails temporarily to the ground or earthed conductive structures in the environment, but in so doing
2. to reduce, as far as possible, the period of such a temporary grounding and to shorten the time in which the stray currents are allowed to flow through a conductive pathway and, consequently, to minimize the effects of stray currents.

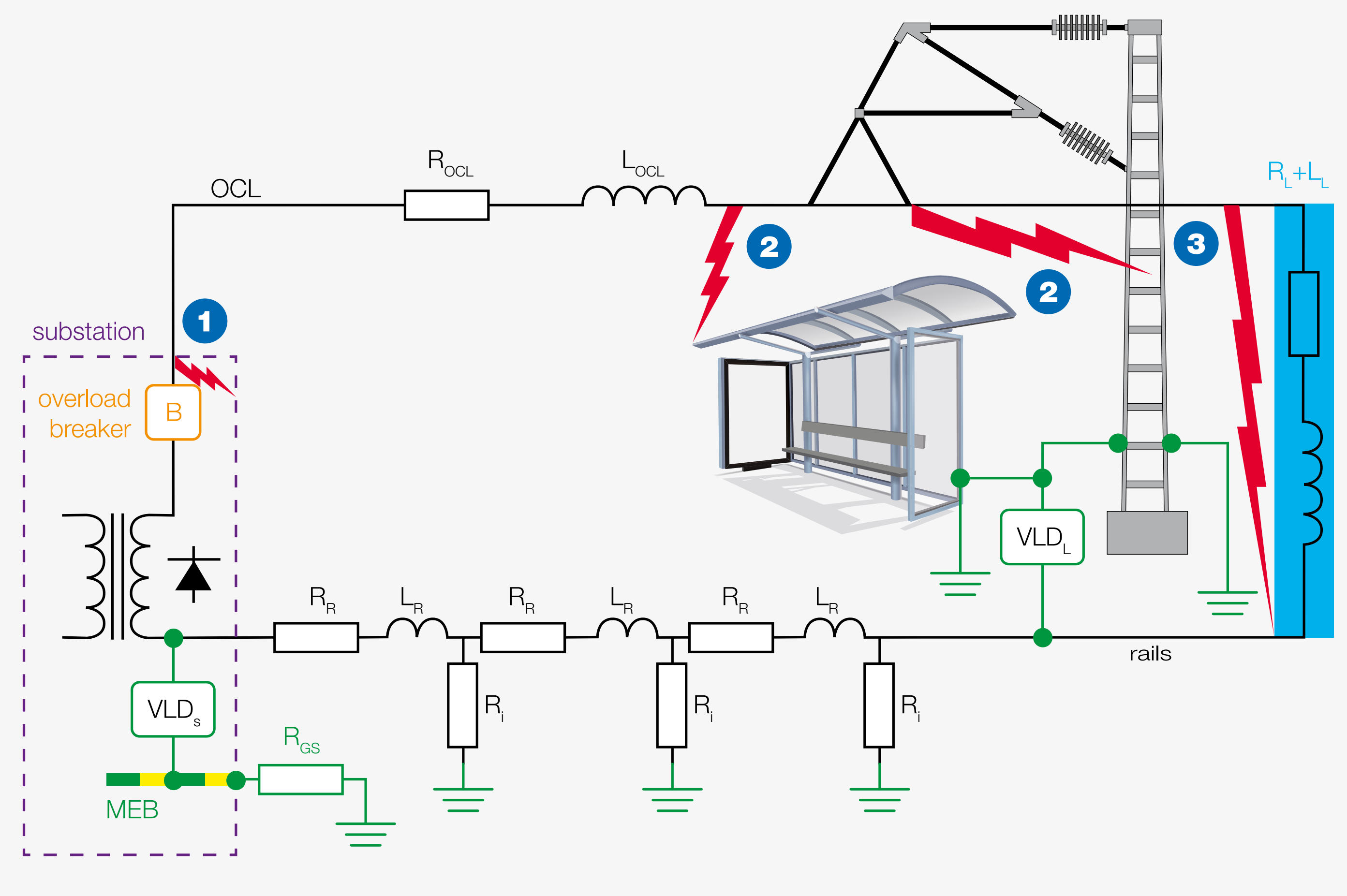
The EN 50526-2 standard divides the VLDs into four classes depending on their design, while defining basic requirements on their operation and characteristics. The EN 50122-1 and EN 50526-3 standards define the types of VLDs according to their function (VLD-F and VLD-O) and specify methods for using these. SALTEK offers three series of VLDs, which fully cover the needs of using them in various situations. Fig. 3 shows typical failure situations.

❶ This is the case where short-circuit occurs between the power substation output towards the OCL and the substation structure (caused e.g. by power feed wire falling down on the surrounding ground). During such a short-circuit dangerous voltage arise on the electrically conductive parts of the substation, and also dangerous step voltage appears in the vicinity. Properly located and dimensioned VLD_S opens the pathway for short-circuit current which in turn initiates tripping of a disconnector installed at the substation. In case of the power feed wire falling down on the ground it is also the grounding impedance of the R_{GS} substation which enters the current loop, but the protection principle remains the same. However, in such a case it is necessary for the R_{GS} impedance to ensure that the short-circuit current is not limited below the tripping level of the B disconnector, i.e. to provide for appropriate quality of the MEB earthing.

❷ In case of the OCL falling down on the ground or grounded steel structures situated along the railway line (train stop waiting rooms, catenary masts, etc.) dangerous touch and step voltages appear at the failure surroundings. In case no a VLD-F is used in the failure surroundings the things will get complicated by the series impedance of OCL, the value of R_{GS} impedance and the resistance of soil between the failure point and the power supply substation. All these components significantly reduce the short-circuit current, which means that the current loop impedance may be negatively affected by factors such as the distance of short-circuit point to the substation, conductivity of the ground path, adjustment of the VLD_S at the substation, etc. The resulting impedance may achieve such a high value which prevents the B disconnector to react rapidly, and the resulting dangerous voltage may endanger human lifes and equipment installed along the railway. Installation and activation of VLD-F along the railway will replace the R_{GS} and soil path impedances with the rails, which are good conductors, and which will ensure a reliable and rapid reaction of the disconnector installed at the substation.

❸ In case of OCL falling down on the rail or a short-circuit arising in the locomotive the B disconnector responds and operates in a standard mode. It is necessary, however, to properly define the relationship between the whole impedance of the traction circuit, the rated voltage of the railway traction and the tripping current of the B disconnector. If the overhead feed conductor falls down at a remote point where the safe touch voltage arising on the rail impedance between

Fig. 3 Typical failure situations arising in traction circuits of a DC powered railway line.

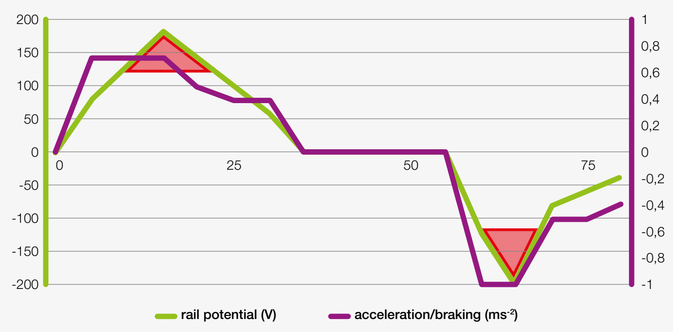


the impact site and the substation ($\Sigma(R_R + L_R)$) caused by short-circuit current flow might be exceeded, it shall be necessary to reduce the voltage level by temporary grounding of the rails using VLD_L devices (in fact there is a parallel current path created). By choosing properly the reaction voltage of the VLD_L and placing these along the railway, it is possible to protect even longer railway sections and structures installed along the line. However, it is always to ensure that the sum of the reaction voltage of the VLD_L and voltage drops on the section between the VLD_L and the failure point shall be below the limit of permissible voltage specified by par. 9.3.2 of EN 50122-1 standard (in relation to the longest time response interval of the B disconnector).

By comparing the functioning of the VLD_L in 2 and 3 situations it can be concluded that in various situations the VLD is exposed to the effects of both voltage polarities, resulting in the necessity of using bipolar VLDs.

As already mentioned, dangerous voltage potentials may arise on the rails, and consequently on the trainsets also during normal train traffic, primarily due to voltage drops caused by the return current flow through the rail impedance $\Sigma(R_R + L_R)$ between the locomotive and the power substation. Fig. 4 shows an example of time profile of voltage present on the rail during the acceleration of a train leaving railway stations in which there is no power substation installed, i.e. where the impedance of the return circuit (the rails) is relatively high. During intensive train acceleration (or during regenerative braking) voltage potentials appear on the rail which exceeds the safe value, and this must be encountered by protective VLD-O installed at critical points of the railway (where persons are endangered by excessive touch voltages which mostly is the case at the railway stations). Sections highlighted in red represent the length of time periods with the occurrence of dangerous touch voltages which need to be treated using VLD-O. In systems with regenerative braking the use of bipolar VLDs is mandatory.

Fig. 4 VLD reaction during acceleration and braking



Example of a rail potential increase (Volts) during train acceleration and regenerative braking (m/s²), arising at a higher distance from the power supply substation, with designated area in which the VLD-O becomes enabled.

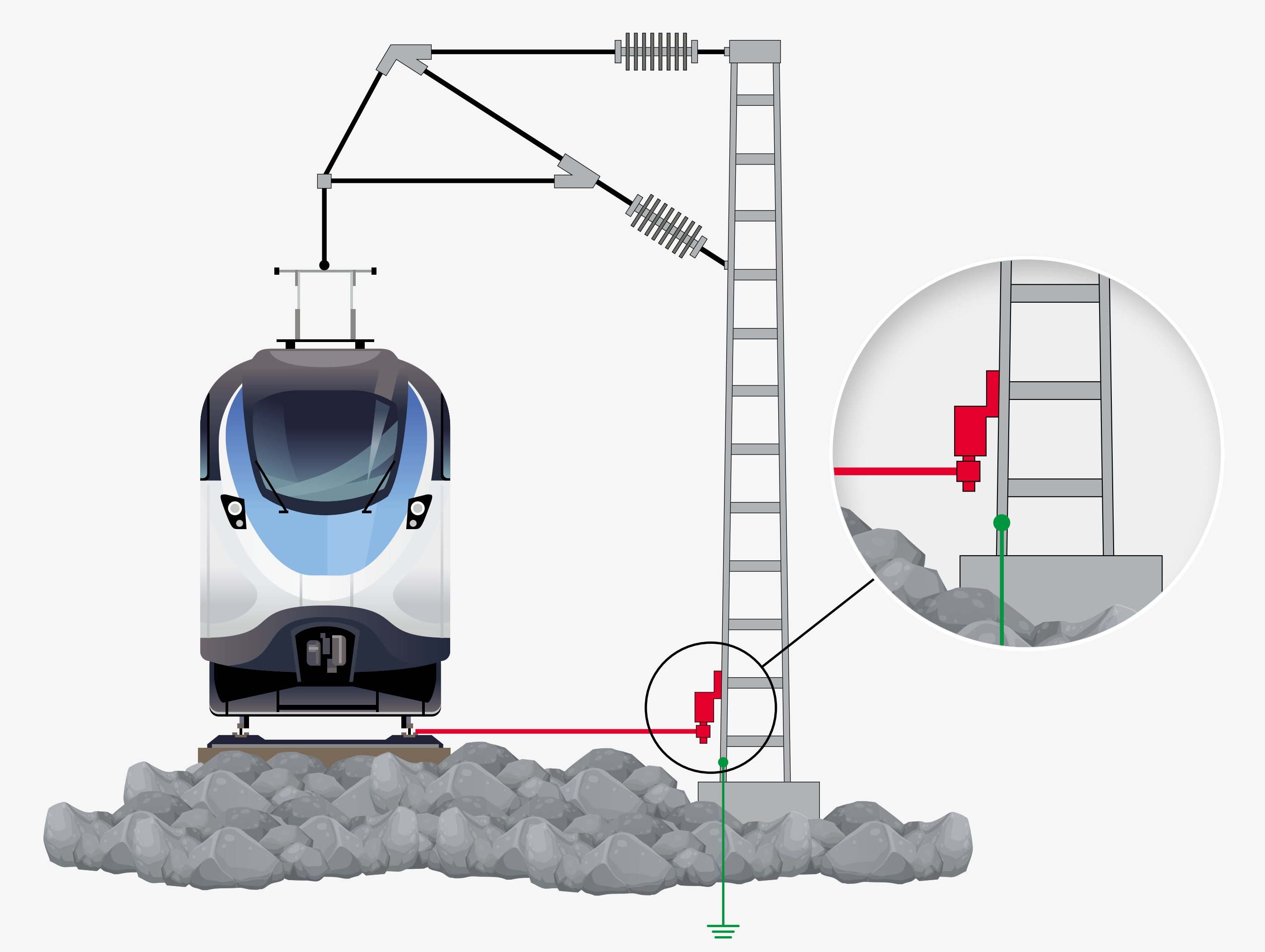
Simple VLD of class 1 (VLD-F)

This low priced VLD of the SCG series has been developed with the purpose of providing basic protection to railway sections affected by OCL fallen down on electrically conductive structures or the ground, or arising during insulation failures between the OCL and other conductive structures erected within the overhead contact line zone (OCLZ). Aside from these applications the VLD-F can be used wherever a combination with protections against atmospheric overvoltages is required. The electric characteristics of these VLDs are set to ensure that the VLD enters into conducting state if the chosen ignition voltage becomes exceeded and, simultaneously, the VLD is able to recover its state for short-time currents of atmospheric overvoltages, i.e. as long as the electric charge of the lightning current is drained, the VLD restores its high-impedance condition.

On the contrary, if a failure occurs on the OCL and subsequently a short-circuit current starts to flow, the integrated short-circuiting bypass provides for permanent short circuit between the SCG terminals which is accompanied with a proper reaction of disconnectors installed at the corresponding substation, i.e. meeting the declared function of the VLD-F. For example, the tripping currents of DC disconnectors in 600 V (740 V) tramway traction lines are within the limits of 3 kA to 4.5 kA, depending on the length of the powered section and the expected number of trams in the section concerned. The SCG series of patented short-circuiting devices is able to safely disconnect the power supply line within the whole scope of the above short-circuit currents. The general objective is to design the traction system in a way to attain a state in which the VLD responds to only a minimum of situations, and to minimize the flow of stray currents.

In case a very short time periods are achieved between the moment of OCL failure occurrence and the power supply disconnection, e.g. by using disconnectors with rapid response, the SGC series of VLD-F devices with higher ignition voltage can be used. This purpose is met by VLD-F devices with ignition voltages of 250 V or 480 V (SCG-250-

Fig. 5 VLD-F (SALTEK SCG series) and its usage in tramway traction powered with <750 V DC.



250 or SCG-250-500, respectively). In this configuration the activation of VLDs caused by the occurrence of short-time voltage peaks on the return conductor (rail) is significantly limited, and the stray currents are reduced to a minimum. When choosing the ignition voltage the time dependence of the permitted touch voltage needs to be considered (i.e. the longest response time of the B disconnector) as per EN 50122-1 requirements.

It should be noted that the VLD-F principle consisting of permanent short-circuit in class 1 has a distinct disadvantage, resulting from its operating principle and the requirement of EN 50526-2 standard. Once the short-circuiting device (earthing switch) trips the VLD of class 1 remains permanently in low-impedance condition, even after the failure cause has been resolved and after recovery of normal traffic on the railway section. This means that the relevant railway section remains permanently grounded and, accordingly, a channel for stray currents remains open. At areas, where this could mean a danger to buildings and infrastructure, it is necessary to regularly check the condition of VLD-F (in particular at the area where a failure has been notified), and replace the short-circuited VLD-F with new ones.

Therefore it is often more efficient (in particular from the operational point of view) to use on the VLD-F position voltage limiting devices of class 2, such as the recoverable VLD-O+F, as a little higher CAPEX at the beginning is soon enough offset by savings in the OPEX. If there is a communication infrastructure available in the vicinity of the installed VLD, it is appropriate to monitor the condition of the VLD by a current sensor via the SCADA system that in a timely manner informs the operator on the necessity to replace the VLD when overloaded. At the moment when the VLD-F remains permanently in conductive state, the statistics of the mean value of currents flowing through the VLD significantly changes, which make it possible to respond in due time and by replacing the VLD to cut down the stray currents flow without the necessity of physical and electrical inspection of the VLDs used in the railway system concerned.

Sophisticated VLD of class 2 (VLD-O+F)

The VLDs class 2, SALTEK product series BVL (bi-directional) are autonomous (i.e. without the necessity to be powered externally) overvoltage limiting devices used in fairly large numbers in DC railway traction. These VLDs have been designed with the objective to carry over largest amounts of failure and short-circuit energy in the mode of repeatable VLD-F, to respond quickly also on overvoltages caused by railway traffic in the VLD-O mode, and in crucial cases such as delayed response of power supply disconnectors or extremely high short-circuit currents, to operate even as a non-repeatable VLD-F.

The response repeatability of VLDs of SALTEK BVL series predetermines them for use in systems where, in addition to the priority of safety, it is necessary to limit the leak of stray currents. If so specified the BVL series gives significantly better results as against the SCG series, or in comparison with another competitive products of class 2. The performance of this product series is further enhanced by the integrated surge arrester of type A2 (MOV) which reacts extremely swiftly to atmospheric overvoltage impulses, but also to steep peaks of traction system´s failure pulses caused by inductive component of the traction system impedance. At the same time it protects the internal electronics of the semiconductor part of VLD from damage.

Steep voltage pikes may arise in modern DC transport systems using regenerative braking as a source of energy between the running trains or in new drive units equipped with IGBT DC/AC inverters, etc. The SALTEK VLD of type 2 is based on sensitive electronics (EDC) that evaluates instantaneously the voltage level on VLD terminals and once this is exceeded it switches, with a small delay of typically 1.5 ms, a power thyristor which takes over the load from already operating power varistors that start to switch within 10 µs from the moment the permitted voltage is exceeded.

Unidirectional version of UVL operates with one set of EDC + thyristor + A2 MOV and responds to one overvoltage polarity, only. This economical version is suitable for use in older and simpler traction systems, serving in the capacity of VLD-O, where voltage peaks of negative polarity are either totally absent or very infrequently encountered and where the VLD-F complex function is not required. The bidirectional version of the BVL series uses anti-parallel combination of two power thyristors controlled by separate EDC systems and completed with A2 power varistor responding quickly to steep traffic or atmospheric voltage peaks. Fig. 6 shows a typical response of UVL/BVL to an overvoltage pulse.

Fig. 6 Oscillogram showing the response of BVL/UVL during the simulation of a steep high-energy pulse

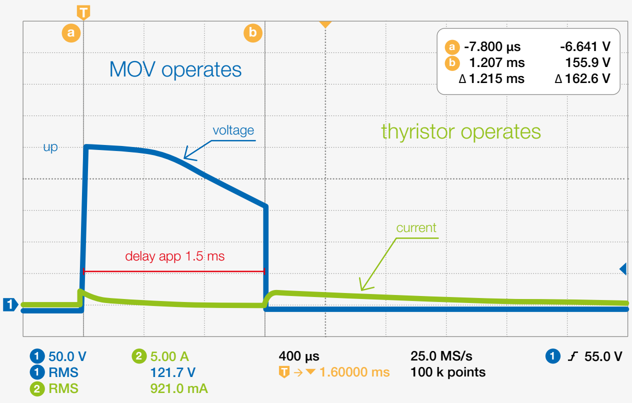
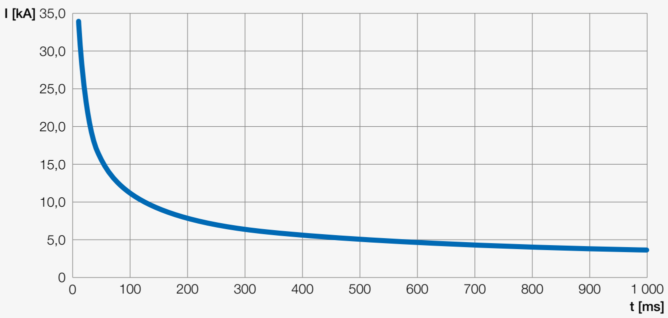


Fig. 7 Load chart of UVL/BVL



BVL – maximum current vs. time

Fig. 7 shows a load chart of SALTEK VLD class 2 of BVL/UVL series. From the above it is clear that aside from very high short-time currents this VLD is able to repeatedly switch current values ranging at the area of shirt-circuit tripping characteristics of modern disconnectors of substations for the powering of lightweight trams and trainsets. It is apparent that if the disconnector used to cut off failure currents is set to 4 kA to 4.5 kA, i.e. typical overcurrent tripping values of smaller power supply substations for trams, the BVL technology is able to co-operate with rapid disconnectors even in repeatable mode, and in such a case it can be used as repeatable VLD-F not only along the track but under certain conditions even in the traction substation where the use of multiple times more expensive VLDs of class 4 is commonly recommended.

Taking into account that it is not necessary to provide any single mast or metallic structure at the OCLZ area with a VLD, but interconnect a multiple of conductive structures with each other by bonding and then to connect them to the rail via a suitable VLD, it may be argued that in such a way it is possible to treat effectively the whole DC tram or lightweight train traction system with a significantly lower CAPEX compared to other expensive systems. Minimum deployment configuration of VLD in the mains should include a VLD mounted between the negative power supply pole (the rail) and the earth (MEB) in each substation, and between the rail and the earth at each of the railroad stop. Of course different maximum currents must be considered for failures (short-circuits) originating close to the substation, where also the parameters of the substation as such have to be considered, while other electric current maxima will be registered for failures (short-circuits) at areas distant from the substations where the maximum current will be reduced by the impedance of the power supply loop, in particular the OCL.

When using VLDs in the underground network or DC railways with heavy train loads it should be noted that the operating characteristics of heavy trains are offset to higher electric current values. In practice it means significantly higher currents during the starting (accelerating) stage (and also the braking) of the train and, consequently, higher short-circuit current tripping limits of disconnectors installed at the substations. In a very accurately designed and realized traction system it is possible to ensure the overvoltage protection with VLDs of class 2 (BVL) installed at rather lightly loaded nodes. Such a deployment, however, should by modelled using an appropriate software, taking into account every possible combination of operating states during periods of concurrent operation of trains at the commonly supplied railroad section, or verify its efficiency in the test run. The combination of acceleration and braking of a multitude of trainsets at the same time at various points of the route sector may reveal significant voltage and current pulses of a longer duration, the value of which may attain hundreds of Amps and approach 1 kA, during time periods of dozens of seconds. In such cases it is necessary to provide the protection with more powerful VLDs of class 3 or 4.

Smart VLD of class 4 (VLD-O+F)

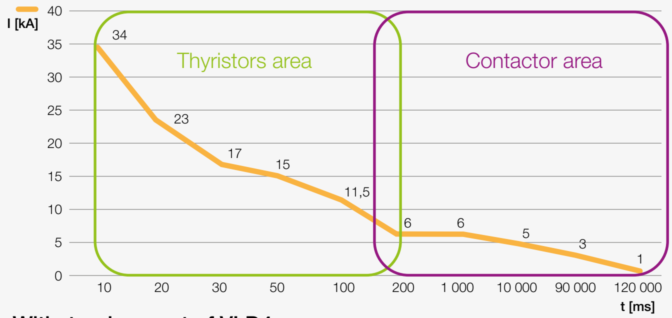
SALTEK has in its portfolio powerful VLD products of class 4 – PVL series. In its design all the currently known requirements of electrified railways on powerful, modern and interactive VLDs have been taken into consideration. In the development of this product SALTEK has chosen a unique concept based on the combination of autonomous VLD class 2.2 with electronically controlled current bypass. This allows to ensure highest possible level of reliability and personal protection in various operational and emergency situations while minimising the energy of stray currents.

The integrated BVL (bi-polar VLD of class 2.2 with integrated A2 surge protection device) responds as first to the exceedance of permitted touch voltage level and is capable of chanelling the high initial energy of atmospheric discharge or failure (short-circuit) current. That is a huge benefit of this concept since the basic functions of VLD-O+F are at any time ensured if a failure occurs in some part of the VLD4 (e.g. the controlling microprocessor, running software, mechanical bypass, etc.). Compared to conventional solutions with permanent short-circuit of the VLD during similar situations, when the return circuit during the maintenance or lockout is all the time connected to the ground (with stray currents leaking), the PVL remains all the time in high-impedance condition and reacts as a standard VLD of class 2, i.e. only when the safety voltage level is exceeded. Permanent short-circuit on the connecting terminals of the PVL is automatically established only in the event of power outage or manually. Emphasis on highest operational reliability which SALTEK focuses in all its products is accentuated by the possibility of automatic power supply backup of the VLD. This may be effected by integrated system of power supply sources in 1+1 automatic backup configuration, not only for AC 230 V power supply, but also for a combination of power supply from station batteries (e.g. AC 230V + DC 48V) or any other specific power supplies. The energy source failure is indicated remotely.

In a normal state (i.e. at the presence of auxiliary power supply) can the software logic of the control PLC, thanks to the permanent voltage and current sensing at the VLD terminals, connect the parallel bypass to the integrated VLD 2 and in such a way increase the long-term current-carrying capacity of the system. The bypass is connected only when necessary, i.e. if the energy capacity of the solid-state VLD 2 is exceeded. This will prolong the life of the whole VLD. The possibility of forced short-circuiting of the VLD terminals, whether by forced electronic closure of the bypass from the VLD4 panel or by manually controlled mechanically lockable earthing switch can be used for a complete safeguarding of persons carrying out the maintenance works. Short-time and long-time limiting curves of load carrying capacity are shown in Fig. 8.

From the above maximum load curves it is apparent that the PVL-1000 is capable of processing electric currents of up to 3.5 kA within time intervals of approx. 30 seconds (which is the average acceleration or braking time during which the VLD4 must be able to bear high current load), which sufficiently covers all traffic situations.

Fig. 8 Limiting curves of load-carrying capacity of PVL-1000

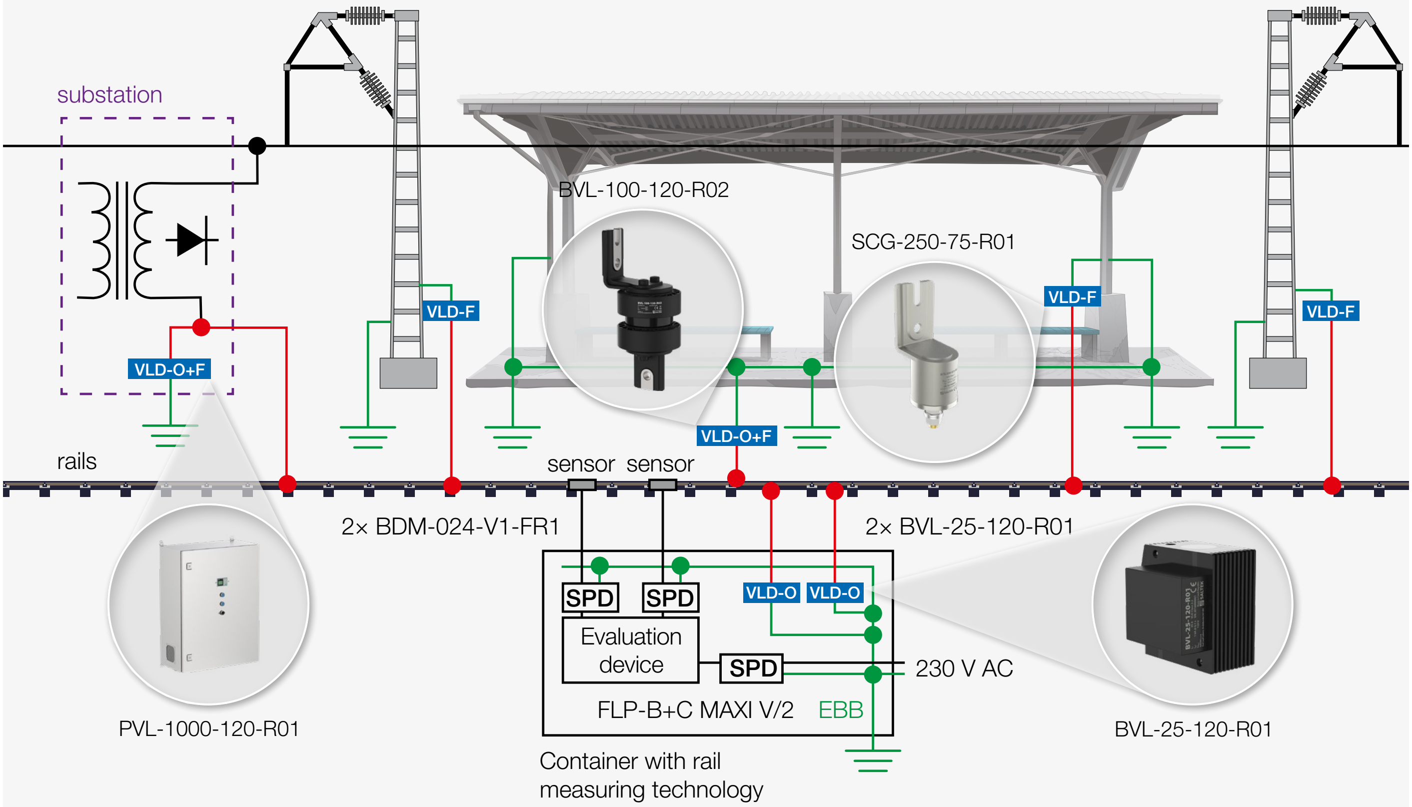


Withstand current of VLD4.x

Also the bypass breaking is controlled electronically in a way to prevent pumping (switching ON and OFF) of the current relay, and to shorten the ON time (the period during which the path for stray currents is open) to a minimum. The behaviour of the whole VLD4 is optimized by software to common operational requirements. However, SALTEK is also able to satisfy specific customer needs and to adapt the VLD characteristics to the client´s specific traffic needs.

Interactivity of PVL-1000 is a significant part of modern railway equipment. Monitoring and remote control of PVL-1000 is ensured by communication with the control centre using standard Ethernet communication interface with the most

Fig. 9 Typical installation of VLDs along the railroad.



commonly used MODBUS protocol (via TCP/IP). This approach makes it possible to remotely scan not only the basic state of the node (instantaneous voltage and the current flow), but also the status of some important elements of the VLD and the VLD as a whole, e.g. using the SCADA system, and at the same time set the performance characteristics of the system incl. the possibility of the so called forced modes, i.e. remote switching ON the VLD. Information thus obtained may then be analysed using suitable software. So, the PVL-1000 may serve both as protective but also monitoring element of the traction system node. Of course, the option of manual control directly from a VLD interactive panel is also available. Compared to many similar products the PVL-1000 stands out by its low weight and integrity, so that it is well-suited for mounting in confined spaces of container-type traction substations, railway tunnels, etc.

The PVL-1000 is typically used at places where dangerous voltage potentials may arise during acceleration or braking of heavy trainsets (in particular at a greater distance from the traction substations), in systems using regenerative braking of trainsets, both as a power source for other trains or energy reconversion back into the power supply mains, in DC traction substations, in section disconnectors, at train stops or railway stations, railway workshops, etc. Some chosen typical examples of using various types of VLD are shown in Fig. 9 (of course, there are a lot of other examples as well).

SALTEK guarantees high reliability, quality and long life of its voltage limiting devices, combined with comprehensive customer support in design, testing and operation. More information about these products can be found at www.saltek.eu or obtained by personal contact at our technical support department.

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