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White paper

Solid-state DC breaker in traction systems

With specialist knowledge and an extensive range of components for direct and alternating current, Astrolkwx's Power Electronics division provides solutions for modern energy challenges.

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Solid-state DC circuit breakers in traction systems

Modern electrified railways face increasing demands for safety, reliability, and efficiency. Conventional electromechanical breakers struggle to meet these requirements due to slow response, arc persistence, and limitations in handling bidirectional currents from regenerative braking. Solid-State DC Circuit Breakers (SSCBs) provide ultra-fast fault interruption, bidirectional protection, and improved operational continuity. This paper explains SSCB technology, illustrates applications in rolling stock and traction infrastructure, and references international standards such as IEC 60947, IEC 60721, EN 50123, and EN 50152. It is written to inform engineers, railway operators, and traction companies about both the technical and practical benefits of SSCBs.

Introduction

Electrified railways form the backbone of contemporary integrated transportation systems, offering benefits such as a large traffic volume, high efficiency, low pollution, and reduced transportation costs[1,2,3].

Significant transformations are taking place in the railway sector, both in Europe and globally. This encompasses the connection between railways and industry, intermodal competition, interoperability, the 2010 liberalisation of railway passenger traffic, and the potential future development of High Speed rail in the USA, South America, the Middle East, India, and beyond. This implies that railway undertakings will need to alter their approach to bidding for new high-speed rolling stock[4].

The various electrification designs that represent historical, geographical, and operational aspects of several nations define the European traction system. Both AC and DC systems are used by mainline railways: France, the UK, Spain, and much of Eastern Europe utilize 25 kV 50 Hz AC, whereas Germany, Austria, Switzerland, Norway, and Sweden use 15 kV 16.7 Hz AC. Urban and suburban rail is supplied concurrently by vast DC networks; 750 V DC is frequently found in trams and metros, 1.5 kV DC is widely used in the Netherlands, southern France, and portions of the United Kingdom, and 3 kV DC is utilized in Italy, Belgium, Poland, Spain, and other nations.

There are typically two ways to categorize traction systems: Infrastructure-side traction systems and Rolling stock-side traction systems.

In order to meet national operator demands and harmonize European standards (such as EN 50123 for DC switchgear and EN 50152 for AC), rolling stock and infrastructure providers must build adaptable traction equipment and protection measures. The end result is a complex and technologically advanced environment where circuit breakers are essential to maintaining interoperability, safety, and dependability throughout Europe's electrified rail networks.

Circuit breakers in European traction systems

For the safe and reliable functioning of European traction systems, which incorporate various AC and DC electrification schemes, circuit breakers are crucial. AC networks utilize high-voltage vacuum and SF_6-free breakers to safeguard substations and feeder lines, replacing older SF_6-based equipment to enhance reliability and meet environmental standards[8].

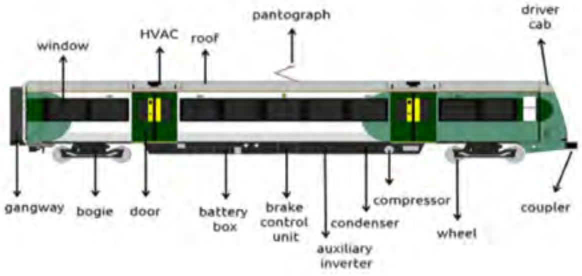

Fig.1: Component of rolling stock

In DC networks, fixed high-speed circuit breakers (HSCBs) safeguard using electromechanical designs that incorporate arc chutes and magnetic blowout coils[9].

Protection systems used in rolling stock are adapted to the operating voltage and functional needs of the train. These consist of advanced solid-state circuit breakers (SSCBs), electromechanical HSCBs, and hybrid breakers that combine mechanical and semiconductor components. SSCBs improve protection performance, decrease downtime, and increase maintenance efficiency throughout contemporary traction systems by offering ultra-fast interruption, arc-less switching, continuous condition monitoring, and predictive diagnostics.

Semiconductor technologies in rolling stock

In order to transfer energy from the electrical supply (catenary) to the traction motors, railway traction systems use a variety of converter stages.

To accommodate various existing networks, train traction systems are frequently used multivoltage systems. When using a DC supply, the rheostatic chopper and the three-phase inverter are connected straight to the line via a filter. In the event of an AC supply, a transformer and rectifier stage are installed.

The main components of the various converter stages are the same power semiconductor devices, despite the fact that they have entirely distinct jobs and mission profiles. Therefore, power semiconductor devices are essential for raising a whole traction system's power-to-weight ratio[10].

Energy conversion, motor control, braking, and onboard power systems are all managed by semiconductor technology in rolling stock, which includes power electronic devices and control semiconductors. High reliability, compact designs, and effective traction are made possible by these technologies in railway applications.

History of semiconductors technology in rolling stock

Initially, rectifiers for traction motors were the only semiconductors used in rolling stock. A major breakthrough was made possible by the development of silicon-controlled rectifiers (SCRs), which improved motor speed and torque control.

Rectifiers increased control and efficiency, but they also brought with them technical difficulties like thermal stress, electromagnetic interference (EMI), harmonic distortion, and integration difficulties. Designing dependable, effective rolling stock systems requires an understanding of these difficulties[11,12].

Modern electronics have greatly improved over the past 20 years as a result of the development and implementation of more turn-off power semiconductor parts starting around 1975. These include MOSFETs, GTOs, IGBTs and enhanced bipolar transistors (with fine structure and lower switching times)[13].

The efficiency and controllability of GTOs were restricted in high-power applications such as traction and industrial drives due to their low switching speeds, high switching losses, and complicated gate-drive requirements. GTOs needed extensive cooling systems, substantial snubbering, and intricate, high-power gate-drive circuits[14,15].

Major challenges included controlling thermal stress and guaranteeing dependability in challenging working environments since devices were prone to overheating and needed sophisticated cooling systems[16]. Furthermore, these converters' electromagnetic interference (EMI) and harmonic distortion impacted surrounding signaling equipment as well as power quality[17].

Some of these restrictions were lessened with the advent of the insulated-gate bipolar transistor (IGBT) in the late 1980s, which offered a higher switching frequency and easier gate control. However, early IGBTs introduced new issues with thermal management, voltage transients, and high manufacturing costs[18].

The power MOSFET has been utilized for low-voltage, high-frequency applications since it was created in the 1970s utilizing Metal-Oxide-Semiconductor (MOS) technology that was first created for CMOS integrated circuits. Since the power bipolar transistor is a current-driven device, large and costly control circuits were required even though they had been widely employed for motor applications in the 1970s and 1980s.
This is why the IGBT took the place of the power bipolar transistor in the 1990s.

Nevertheless, this period saw constant improvements in semiconductor materials, packaging, and control algorithms, which set the groundwork for the incredibly effective and small power electronic systems that now rule electric traction and motor drives.

As PWM control advanced in the 1980s and 1990s, digital control hardware, space-vector PWM, and enhanced carrier algorithms made it possible to precisely modulate voltage and frequency for AC motor drives. The introduction of synchronous and asynchronous (induction) motors in traction applications was directly influenced by these advancements, which also made variable-frequency drives (VFDs) feasible at high power[19].

The IGBT, which was developed in the late 1970s and early 1980s and went on sale in the 1980s, took over as the most popular power switch in the 1990s. By combining bipolar device current capabilities with MOSFET-like gate drive ease, IGBTs allowed for simpler gate drives, faster switching than GTOs, and a lighter system. By the 1990s, traction inverters could now easily access and afford second-generation, more durable IGBTs with better safe-operating regions and lower latch-up.

Traction manufacturers quickly switched to inverter-fed AC traction (induction and synchronous motors) with IGBTs and sophisticated PWM control. Better high-speed performance, lower maintenance, and increased dependability were all provided by AC traction. IGBT-based inverters were used in a considerable number of new AC locomotives and EMUs in North America, Japan, and Europe during the 1990s[20].

Despite the benefits, early IGBT systems required strong protection against overvoltage, careful thermal control, and EMI mitigation. In order to satisfy traction reliability requirements, power module packaging, cooling, and gate-drive protection underwent significant evolution during this decade.

Due to various production issues, these early IGBTs had comparatively high failure rates. However, by completely regulating each stage of the production process, contemporary semiconductor manufacturers were able to accomplish zero defect production.

With their faster switching frequencies, reduced power losses, and enhanced thermal performance, Silicon Carbide (SiC) MOSFETs have become a next-generation substitute in recent years, enabling lighter and more energy-efficient train designs. SiC-based traction inverters have already been used by a number of manufacturers in new high-speed and commuter train models, including Hitachi, Toshiba, and Siemens[21].
However, because of their high-speed switching and compact design, Gallium Nitride (GaN) transistors are being investigated for use in auxiliary converters and onboard DC/DC systems. However, because of voltage constraints, they are not currently appropriate for main traction circuits[22].

In general, rolling stock power electronics are gradually moving away from conventional IGBT-based systems and toward SiC and GaN technologies, which allow for increased lifespan performance, decreased weight, and more efficiency in contemporary railway applications.

Problems in protection systems for traction systems

Number of technological issues that is being faced by Traction systems:

A: Problems with coordination in multi-converter systems

Auxiliary inverters, onboard DC link circuits, and several traction converters compose modern rolling stock, which is frequently connected by common power buses. Because failures in a single converter might spread over shared DC lines before being isolated, this dispersed architecture makes protection coordination difficult. Train availability may be decreased by needless tripping of healthy circuits caused by inadequate differentiation between internal and external problems. Because power electronic converters require ultra-fast and selective protection due to their low short-circuit tolerate capabilities as compared to typical electromechanical devices, achieving selectivity in fault clearing is especially challenging[23].

B: Rapid Transients and High Frequencies of Switching

At very high switching frequencies (up to tens of kHz), modern traction converters based on Silicon Carbide (SiC) MOSFETs and IGBTs produce rapid transient overvoltage and current spikes. These transients produce steep di/dt and dv/dt waveforms that frequently outperform the response capabilities of conventional electromechanical and thermal-magnetic protection systems. As a result, protective systems might not respond quickly enough to unexpected insulation failures or short circuits, which could cause converter damage or fire threats. High-frequency noise can also interfere with sensors and protection relays, causing false trips or failing to detect real failures[24].

C: Power flow in both directions from regenerative braking

The traction network experiences bidirectional current flow due to the extensive usage of regenerative braking. Conventional protection systems, which are mainly made for unidirectional current, could mistakenly perceive reverse current flow as a fault condition or, on the other hand, miss real problems that happen during regenerative operation. Setting overcurrent and directional relays is made more difficult by this bidirectionality since protection thresholds need to dynamically adjust to both motoring and braking modes. Lack of such adaptive methods may result in unintentional trip commands during routine braking operations or delayed fault clearance[25].

D: Limitation of fault current and DC arc faults

In DC traction circuits, straightforward arc extinction is not possible since there are no natural current zero-crossings. Arc persistence can cause damage to cables, contactors, and converters by maintaining high fault currents after a fault has occurred, even after isolation attempts. In order to effectively extinguish DC arcs, mechanical circuit breakers frequently lack the speed and control accuracy required .In rolling stock, high-capacitance DC link systems have the potential to discharge quickly during faults, producing enormous inrush currents that surpass the ratings of safety devices. Effective fault current limitation is therefore still a key design consideration[23].

E. Electromagnetic interference and communication

New problems including delay, synchronization errors, and EMI are brought about by the use of digital protection relays and communication-based coordination. Significant EMI is produced by high-frequency switching of traction inverters, which can interfere with data transfer between protection units and onboard controllers. This interference may cause safety-critical systems to malfunction or delay relay response. For dependable protection, maintaining communication integrity in such loud settings continues to be a major difficulty[24].

F: Challenges with reliability and maintenance

The lifespan of protective devices is shortened by frequent load cycling, vibration, and temperature changes, which hasten component degradation. Unexpected equipment failures and service outages result from traditional maintenance procedures, which are frequently reactive rather than predictive.

G: Detection of faults and selectivity in distributed networks

Traction networks frequently span long distances, utilizing high-inductance feeder lines (measured in MH/km). As a result of high line inductance, voltage oscillations and transient overvoltage can occur during switching events or faults. This complicates the quick and selective detection and isolation of faults by relays and circuit breakers . Inadequate coordination among substations can cause multiple feeders to trip at the same time, which may result in extensive power outages. Guaranteeing fault selectivity in a distributed infrastructure is still a significant challenge, especially when mixed AC/DC systems are used within the same network.

H: Harmonics and issues related to power quality

High-power converters in rolling stock introduce harmonics into the traction supply network, where they interact with line and transformer impedances, resulting in overvoltages, resonances, and distorted current waveforms.

These power quality issues can diminish the sensitivity of protective devices, lead to nuisance tripping, and hasten the aging of insulation and substation equipment [25]. It is crucial for dependable safeguarding to handle harmonics and sustain high power quality.

I: Inductance Problems in Traction Systems

Line inductance (MH/km) is a measure of how resistant third-rail or overhead cables are to abrupt fluctuations in current. In traction systems, high inductance can be a significant issue since trains use enormous, erratic currents, and rapid fluctuations in current combine with the line's inductance to generate instability, power loss, and voltage drops.

Current ripple is created when pulsing currents from switching devices in contemporary converters (IGBTs/SiC inverters) interact with line inductance.

Ripple currents can increase traction motor wear and decrease the smoothness of motor torque. Particularly when accelerating quickly or braking regeneratively, the inductance of the supply line results in a voltage drop proportional to di/dt × L.

Motor performance may be impacted by lengthy feeder sections when the train pantograph's voltage can drop noticeably.

Distributed capacitance is present in feeders and overhead lines. Power electronics may be harmed by high line inductance because it can create LC resonant circuits that cause voltage oscillations during switching events.

The inductance of the line may restrict current propagation when trains inject energy back into it, decreasing the efficiency of regenerative braking and causing an increase in energy loss.
Signaling and communication may be impacted by EMI and harmonic distortion produced by inductive lines interacting with high-frequency converter switching[23].

Why solid state technology?

Fault interruption

This graph illustrates the basic physics, protection limitations, and technological trade-offs of several DC circuit breaker designs while depicting the dynamic interruption of a DC short-circuit fault current in a DC traction system.

The lack of natural current zero crossings in a DC network leads to a sharp increase in fault current, which is mainly controlled by the DC-link voltage Vdc, resistance R, and system inductance L.

The breaker must actively push the current to zero by adding impedance or counter-voltage to the circuit once the fault (dashed vertical line) has been identified. Because the mechanical DC breaker (blue curve) depends on contact separation and arc elongation, its interruption speed is constrained by arc extinction dynamics and mechanical inertia. As a result, the current decays slowly over several milliseconds, causing high I2t energy, severe thermal stress on conductors, and significant electromagnetic forces on busbars.
In order to minimize fault energy, the solid-state DC breaker (orange curve) employs fully controllable power semiconductor devices (such as IGBTs or MOSFETs) that impose a rapid counter-voltage and cause an almost instantaneous current collapse within tens to hundreds of microseconds. However, during normal operation, this results in continuous conduction losses and significant thermal loading energy, high electromagnetic forces on busbars, and extreme heat stress on conductors.

The hybrid DC breaker (green curve) combines quick protection with low steady-state losses by using fast semiconductor commutation to divert the fault current into an energy absorption path (usually metal-oxide varistors), quickly lowering the current within 1-2 ms. A mechanical disconnector then opens under almost zero current conditions.

Overall, the graph quantitatively shows how interruption duration directly affects fault energy, equipment stress, and system survival, which explains why, despite their greater complexity, hybrid and solid-state breakers are technically better for contemporary DC traction and HVDC systems.

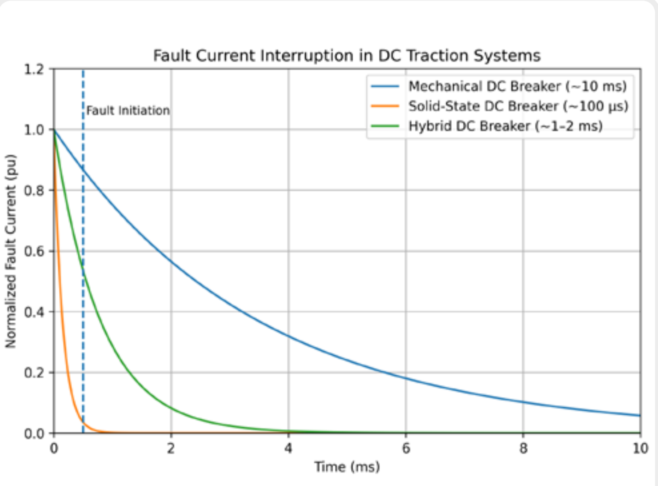

Fig.2: Fault current interruption

In traction systems, the evaluation of conduction losses and efficiency across mechanical, solid-state, and hybrid circuit breakers uncovers distinct performance traits. During normal operation, mechanical circuit breakers (MCBs) demonstrate very low conduction losses due to the current flowing through metallic contacts with minimal resistance (usually under 1 mΩ), leading to a high steady-state efficiency. Nonetheless, their slower switching speed and mechanical wear can have a slight impact on performance over time.Conversely, SSCBs result in a considerable on-state voltage drop of approximately 1–3 V, which causes conduction losses that increase with the current and thus reduces efficiency during steady-state operation. Even with this disadvantage, SSCBs provide switching speeds that are very fast and a long operational life because they have no mechanical components. HCBs merge the benefits of both technologies, enabling current to pass through mechanical contacts during standard operation to reduce conduction losses, while semiconductors manage fault interruption for rapid switching and minimized arcing. Consequently, hybrid breakers exhibit a high level of efficiency akin to that of mechanical breakers, while also offering the advantages of a quicker response and diminished mechanical stress. This makes them the most efficient and balanced option for contemporary traction systems.

MCBs depend on moving contacts and methods for extinguishing arcs, which makes them susceptible to mechanical wear, contact erosion, and degradation as time passes. This leads to increased maintenance requirements and regular servicing to guarantee dependable functioning, particularly in high-frequency switching situations. On the other hand, SSCBs utilize semiconductor devices to interrupt current and have no moving components, resulting in enhanced reliability and reduced maintenance due to the absence of wear from physical contact. Nonetheless, continuous high-power operation can impact their reliability due to thermal stresses and semiconductor degradation. HCBs provide an ideal equilibrium by merging mechanical and semiconductor elements, which alleviates the mechanical strain on the contacts and restricts the semiconductor's duration of high conduction. This design increases overall reliability and reduces maintenance frequency compared to purely mechanical breakers. As a result, hybrid circuit breakers offer the best balance of long-term reliability and lower maintenance needs in contemporary traction power systems.

MCBs use electromechanical tripping mechanisms that are slower and less precise, complicating the attainment of fine selectivity and coordination with other protection devices in complex traction networks. Because of their longer interruption times, upstream breakers may trip unnecessarily, which diminishes the overall selectivity of the system. In contrast, SSCBs offer very rapid and precise fault detection and interruption, which allows for enhanced selectivity and exact coordination with other protective layers. Their electronic control permits adjustable trip characteristics and real-time fault discrimination, ensuring that only the affected section of the traction network is isolated. Combining the quick reaction of solid-state devices with the current-carrying efficiency of mechanical contacts, HCBs offer exceptional selectivity and coordination capabilities. Under normal operating conditions, current travels through the mechanical path, whereas during faults, the semiconductor branch provides quick isolation. By improving fault discrimination, reducing service interruptions, and enhancing protection coordination, this hybrid action establishes hybrid breakers as the most effective option for achieving both speed and selectivity in modern traction protection systems.

Other problems in breakers

The short-circuit fault is classified as either a high impedance fault or a low impedance fault based on the direction and amplitude of the overcurrent. Current gradient protection is used to respond to low impedance short-circuit faults, while differential protection is used to respond to high impedance short-circuit faults. The protection rapidity in low impedance short circuits is taken into consideration by switching between different protection strategies, however the rapidity in high impedance short circuits still need improvement. Transverse protection is employed for radiation DC MG, and a resistance current limiter is added to boost the protection's sensitivity and range.

The locomotive architecture integrates battery subsystems equipped with fuses, disconnectors, and precharge circuits, in combination with a traction converter comprising a bidirectional DC/DC chopper and a crowbar-based protection stage. Within the scope of SSCB, only the hard crowbar configuration—characterized by its inherently low impedance—is of relevance and is therefore denoted as "crowbar" in the subsequent sections .

Activation of the crowbar initiates a direct short across the DC link, which in turn causes the coordinated blowing of all series-connected fuses within the battery strings. This protective action, while effective in rapid fault isolation, leads to a full disconnection and functional collapse of the battery subsystem. Such an event results in extended locomotive downtime and substantial repair or replacement costs.

To avoid this scenario, a fast and wearless breaker between the battery system and the input of the dc-chopper is highly recommended.

In addition to its traditional diesel engine, the Charger B+ locomotive is a multi-system locomotive that uses a traction battery as one of its main energy sources. Depending on the route and operating needs, this design enables the locomotive to function flexibly in a variety of modes, such as diesel-electric, battery-electric, or a combination of both.

However, there are additional difficulties when incorporating high-capacity batteries into locomotive traction systems, especially with regard to electrical safety. The Charger B+ uses a Solid-State Circuit Breaker (SSCB) to solve this. An essential component of power system protection, the SSCB isolates the battery system from the traction converter DC link in the case of a short circuit, regardless of whether the problem stems from the battery or the converter. The SSCB reduces the chance of equipment damage, fire dangers, and downtime by quickly and precisely cutting off hazardous current flows.

SSCB is capable of interrupting overcurrent in both directions, functioning as a standalone bi-directional switch. This inherent capability provides robust protection for the traction battery and the converter, ensuring fault isolation regardless of the current's direction. However, if system-level design considerations emphasize overall cost, complexity, or weight reduction, an alternative configuration could be adopted. In such a case, a unidirectional SSCB could be installed to handle forward current interruption, while a hard crowbar circuit would manage reverse current events. This approach could simplify the SSCB design and potentially reduce system costs, while still ensuring reliable protection of the traction power system.

Moving towards gas free medium circuit breakers

The environmental effects of sulphur hexafluoride (SF_6) in the electrical industry are being aggressively addressed by the Electric Utility Industry Sustainable Supply Chain Alliance (EUISSCA). Given that SF_6 is a powerful greenhouse gas that has a 23,500-fold higher potential for global warming than CO2, EUISSCA works with suppliers and utilities to investigate and promote sustainable solutions.

SF6 is the most powerful and persistent greenhouse gas, despite having good insulating and arc extinguishing qualities for HV applications. SF6 has a 3200-year atmospheric lifespan and a 23 500-fold greater global warming potential (GWP) than CO2 over a 100-year period.

The amount of SF6 installed globally indicates the potential for reducing emissions in the HV industry: 165 tons of SF6 are filled-in within HV live tank circuit breakers annually, assuming only 245 kV, 420 kV, and 550 kV rated voltage. Of these, 33 tons of SF6 are released throughout Europe, highlighting how crucial it is to find excellent, practical substitute dielectric gases in order to reach the climate targets set by the EU.

The European F-gas Regulation (EC 517/2014), which seeks to reduce the EU's F-gas emissions by two-thirds by 2030, amply reflects this. In order to phase out up to one-fifth of 2014 sales by 2030 and encourage industry and research to invest in alternatives, the specific objectives are as follows: I) restricting the total amount of the most significant F-gases that can be sold in the EU starting in 2015; ii) outlawing the use of F-gases in many new types of equipment; and iii) preventing emissions of F-gases from existing equipment through appropriate monitoring, staff certification, and recovery of the SF6 at the end of the equipment's life.

EU SF6 phase-out timeline

The regulation establishes a clear timeline for phasing out SF_6 in new electrical switchgear: New medium-voltage (MV) switchgear up to 24 kV is prohibited as of January 1, 2026. New high-voltage (HV) switchgear up to 145 kV is prohibited as of January 1, 2028. New HV switchgear above 145 kV is prohibited as of January 1, 2032. New SF_6 switchgear is generally prohibited as of January 1, 2035, with a few exceptions.

Crucially, these precautions only apply to new installations; equipment that already contains SF_6 can be kept in use and maintained until the end of its useful life. As of 2035, SF_6 cannot be used for maintenance or servicing of switchgear unless it is recycled or reclaimed or proven that using reclaimed SF_6 is infeasible[26,27,28,29].

With advantages in speed, size, and environmental impact, SSCBs are a good substitute for SF_6 breakers in medium- and high-voltage traction systems. Nonetheless, ongoing research and development is required to overcome issues with voltage ratings, thermal management, cost, and technological maturity. SSCBs have the ability to significantly contribute to the modernization of traction system protection as technology advances.

Advanced solutions

Circuit breaker selection in traction systems

By creating electronic switches (IGBT/MOSFET-based) with quick fault detection and control, integrating them into the current traction system, and making sure they satisfy voltage, current, and protection requirements, vacuum circuit breakers can be swapped out for solid-state breakers in traction systems. Compared to VCBs, this offers protection that is quicker, lighter, and requires less maintenance.

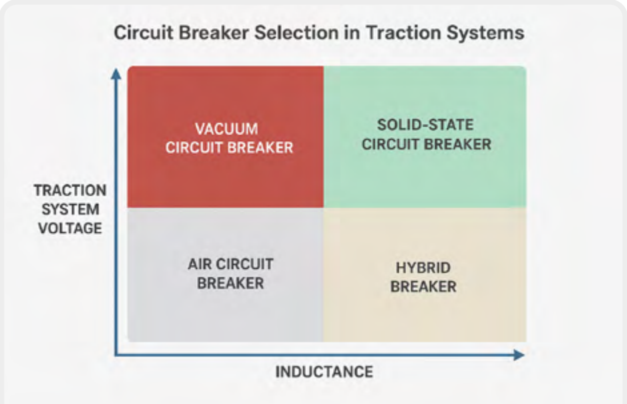

Fig.3: Circuit breaker selection in traction systems

Zone protection

DC traction networks (such as urban metros, light rail, and various mainline systems) are extensive distributed systems characterized by multiple sources, feeders, and intricate return paths. In DC systems, fault currents are continuous (lacking natural current zero crossings) and can escalate swiftly. If they are not quickly and locally isolated, a single fault can: (a) introduce significant I^2t energy into conductors and equipment, (b) lead to tripping of upstream supplies and result in widespread outages, and (c) cause safety issues and stray-current corrosion. As a result, contemporary standards and technical assessments necessitate protection schemes for DC traction applications that are both rapid and selective[30,31].

Solid-state circuit breakers within traction systems

SSDCBs have emerged as a crucial solution to the challenges of fault detection, rapid current interruption, and bidirectional power flow in modern traction systems. Unlike traditional electromechanical breakers, SSDCBs use high-speed power semiconductor devices like IGBTs or SiC MOSFETs to interrupt fault currents in microseconds to a few milliseconds, thus preventing voltage overshoots, arc persistence, and damage to secondary equipment.

SSDCBs within rolling stock

SSDCBs offer swift safeguarding for high-power traction converters, DC link circuits, and auxiliary systems within rolling stock. SSDCBs can isolate faults in microseconds to a few milliseconds, unlike conventional mechanical breakers that usually take tens of milliseconds .This rapid operation is essential for reducing high di/dt and dv/dt transients produced by contemporary IGBT- and SiC-based converters, which can otherwise harm onboard equipment .SSDCBs support bidirectional current flow, which allows for safe operation during regenerative braking and ensures that reverse currents do not disrupt protection coordination. Their compact design is especially beneficial in rolling stock, where space and weight limitations restrict the use of large mechanical breakers. Additionally, SSDCBs in rolling stock can be combined with smart protection systems that provide real-time monitoring of current, voltage, and temperature. With this integration, predictive fault detection becomes possible. This reduces the chances of failure in the converter or motor and improves operational reliability.

SSDCBs within traction infrastructure

SSDCBs are essential components of substations, feeder lines, and extended DC traction networks in traction infrastructure. Voltage overshoots and oscillations can occur during fault conditions due to the significant series inductance (MH/km) of long feeder lines. SSDCBs tackle this issue by swiftly interrupting fault currents before they escalate to harmful levels, safeguarding both substation equipment and rolling stock.

DC networks are where SSDCBs show particular efficacy, as traditional mechanical breakers have difficulty extinguishing arcs owing to the lack of natural current zero-crossing. SSDCBs can extinguish arcs and limit fault energy using power semiconductor devices, thereby protecting cables, converters, and transformers from damage. Moreover, SSDCBs can aid in selective fault isolation within complex networks that contain several parallel feeders, thereby improving the reliability and continuity of the traction power supply.

Role of SSDCBs in mitigating cooling problems

Power electronic components in traction systems, like IGBTs and diodes, are very vulnerable to thermal stress caused by high power densities, pulsed operation, and environmental constraints. Excessive junction temperatures can impair performance, shorten device lifespan, and heighten the risk of thermal runaway. In this context, SSDCBs have proven to be an effective topology for addressing thermal management challenges.

SSDCBs reduces the overall count of power semiconductor devices. Consolidating switching elements reduces overall heat generation and mitigates the formation of localized thermal hotspots. Moreover, the SSDCB topology allows for optimized switching strategies that restrict simultaneous high-current events and minimize dynamic losses, resulting in reduced transient heating of the components.

Another notable benefit of SSDCBs is the more even current distribution across semiconductor devices. It is common for setups with dual converters to show an imbalanced distribution of load, leading to localized overheating. On the other hand, SSDCBs distribute electrical stress among a smaller number of devices, thereby fostering a more uniform thermal profile. Not only does this uniformity boost the reliability of devices, it also makes smaller and more efficient cooling solutions possible. This helps to reduce both the complexity and the weight of the overall thermal management system.

Environmental conditions

For the traction system there is a problem that The environmental conditions are IEC60721-3-5.

The SSDCCB can operate without restrictions in the range of -40 to +46 degree Celsius outside temperature. It can tolerate atmospheric humidity ranges from 5-100% with the service life 30 Years.

Key features of the Astrol solid-state DC circuit breakers

Astrol’s solid-state DC circuit breakers offer substantial benefits in maritime and traction applications, where quick fault isolation and system reliability are essential. These circuit breakers provide strong protection for DC grids and can interrupt faults at an extremely high speed by using sophisticated semiconductor technology, namely Insulated Gate Bipolar Transistors (IGBTs). They can stop faults in just a few microseconds, usually 8–10 µs, which prevents short-circuit situations from worsening and reduces possible damage to the system. With a design that accommodates fault currents of up to 20 kA, they provide dependable protection even in situations where high-current faults occur. With a modular and compact design, the breakers have dimensions that range from 507 × 507 × 673 mm to 507 × 507 × 1017 mm based on the current rating, making them suitable for installation in tight spaces. By improving thermal management, a liquid cooling system allows for higher current ratings while maintaining a compact form factor. Moreover, Astrol’s breakers are modular and system-independent, allowing for straightforward integration into current DC grids without the need for significant alterations.

They come in current ratings of 0.35 kA for low-power applications, 1.5 kA for medium-power systems, and 5 kA for high-power applications. They are certified by DNV, Lloyd’s Register, and CCS, ensuring adherence to international standards. In summary, these solid-state DC circuit breakers provide quick fault interruption, can manage high fault currents, and allow for flexible integration. This makes them a dependable choice for contemporary maritime and traction DC power systems[32].

Conclusion

Solid-State DC Circuit Breakers (SSCBs) signify a revolutionary development in safeguarding contemporary traction systems. Utilizing semiconductor technologies like IGBTs, SSCBs offer ultra-fast fault interruption, high fault current management, and precise selectivity to meet the specific challenges of DC traction networks, where traditional breakers fail due to the lack of a natural current zero.

Designed to be compact, modular, and easy to maintain, they can be integrated seamlessly into both infrastructure and onboard rolling stock, thereby supporting system reliability and operational continuity.

Moreover, SSCBs provide sophisticated features like regenerative energy management and predictive diagnostics, which boost energy efficiency and minimize downtime. As rail networks become more electrified and involve higher voltages, SSCBs are set to play a vital role in guaranteeing the safety, resilience, and efficiency of future traction systems.

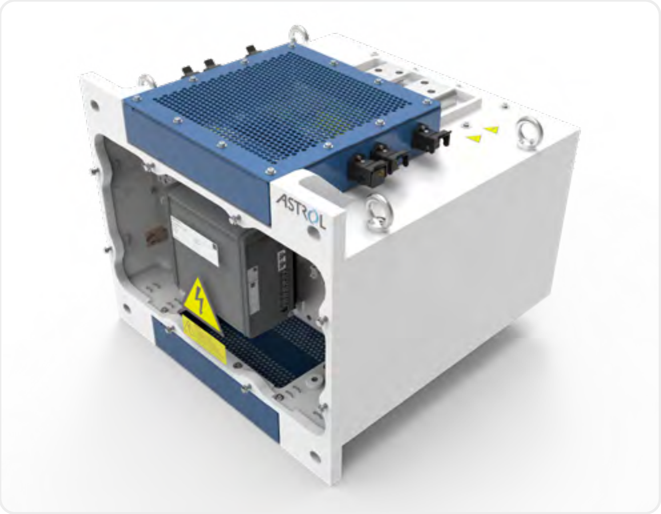

Fig.4: Astrol solid-state Dc circuit breakers

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