White Paper

POWER CONVERSION

MMC FOR RAIL ELECTRIFICATION

The advantage of Modular Multilevel Converter topologies for medium-voltage, high-power applications.

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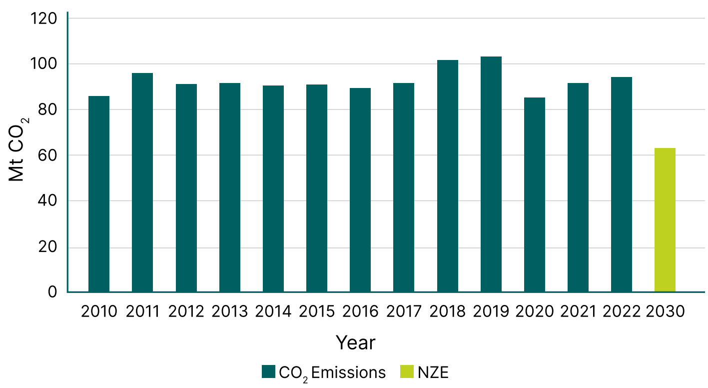
PURPOSE

Introduction and background

Current challenges in the rail segment

Decarbonizing the transport sector is crucial to achieving the Net Zero Emissions by 2050 Scenario (NZE), especially considering that passenger and freight activity is expected to more than double based on current trends.

Rail transportation represents a low-emission alternative to air travel. Although electrification already covers 85% of passenger rail and 55% of freight movements, further expansion of the rail network will be necessary to achieve carbon neutrality.[1]



2030 target to reach Net Zero Emission by 2050

These factors are leading to an **increase of traffic in rail transportation** as populations are looking for ways to reduce their travel emissions. This trend is supported by public investment as the rail operators need increase power capacity, pushing to upgrade old 3 kV DC distribution networks to 25 kV AC.

Large investment programs at countries level are set to develop alternatives to flights and improve interconnection between existing transports systems, which is traduced into new railway lines or electrification of existing rail networks. The TEN-T (Trans-European Transport Network) regulations at both the European and national levels are establishing strong incentives for rail projects that meet key targets for both passenger and freight transport: full electrification of the line, interoperability of energy, long distance rail interconnection for large airports and passenger lines >160 km/h. Some countries go even further by setting their own challenging goals to improve their national transportation system.

Additionally, the **share of renewable energy in the electricity generation mix has increased** at the national level, reducing grid inertia. Consequently, the transient inrush power from trains at local substations is more likely to disrupt the network. As a result, Distribution System Operators (DSOs) are imposing stricter constraints on consumers regarding unbalance voltage and reactive power.

Technical solutions

To increase electrified line capacity in response to traffic ramp-up:

- **High Voltage Boosters** (HVB) can be used to maintain catenary voltage at a level acceptable by the rolling stock, with low impact on the actual installed substations and without the need of a grid connection.
- Upgrade from 3 kV to 25 kV catenary supply. If the substation is far from a strong grid network , a **Static Frequency Converter (SFC)** will be the solution.

To balance high renewable energy penetration in grid energy mix:

- For existing lines, **HV Balancers or STATCOM** for clean power quality on grid connection, with low impact on existing substations.
- For greenfield projects (newly created lines), **SFC** substations can help ensure excellent power quality from the grid, balance power between substations to avoid localized peak power, and facilitate power exchange between trains.

CRITICAL REQUIREMENTS

Long life cycle for products used **> 25 years**

High reliability, availability and strong service support – railway infrastructures are transporting millions of people every year in a city like Berlin. Operators are impacted by any interruption of power, with a negative impact on their public image.

Resiliency to high fault rate on both catenary and grid sides.

Very demanding time response for SFC, which should be able to restart very quickly in case of trip.

SFC TRACTION POWER SUPPLY

An SFC connects a three-phase distribution or transmission grid to a single-phase catenary network. Historically, in some countries, the single-phase railway network operates at a different frequency than the public grid. This difference makes direct connection between the two grids impossible, necessitating frequency conversion.[2] [3

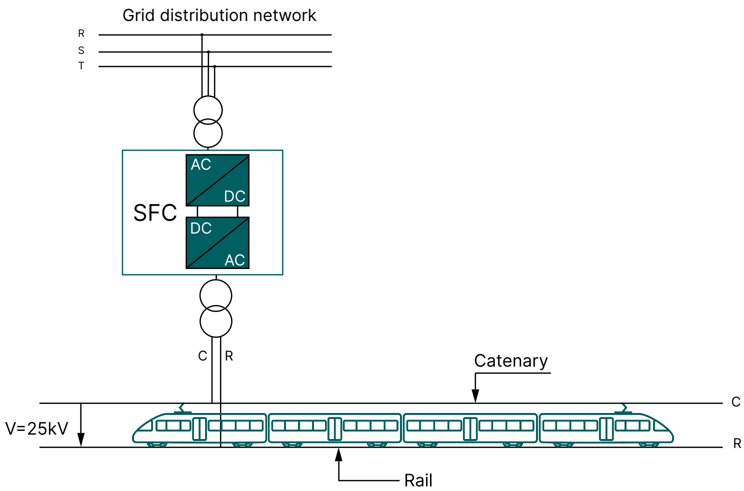
Nowadays, SFCs are also used when the grid network supplying the rail line has limited power capacity[4]. Some new line developments are incorporating SFCs for overall optimization.[5]

To decouple the two grids, an SFC can be installed between them. An SFC offers several features: independent reactive power control on both grids, the ability to feed the railway from a weak three-phase grid with low short circuit power, and perfect voltage balancing between phases.

An SFC essentially functions like a generator for the rail network and thus has similar requirements to traditional generators, such as high efficiency and low losses, combined with a compact and reliable design.

When the catenary network is fed by multiple sources (e.g., in parallel), SFCs balance the power between traction substations, reducing their overall number for example by allowing increased distances between them. To maximize these benefits, SFC substations are integrated with an ECCS Energy Control & Command System (ECCS).

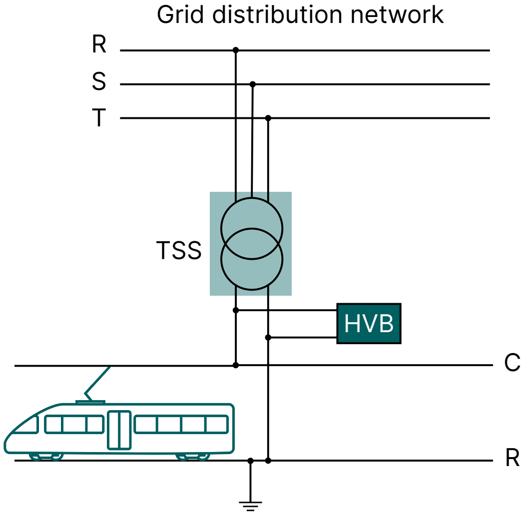
- Provides the synchronization of SFC along the line thanks to the PMU (Phasor Management Unit) such as GE Vernova Multilin N60, helping to balance power between substations.
- Protects the SFC system through the protection & control relays such as GE Vernova Multilin Agile.
- Supervises and manages the entire traction power supply to maximize availability.
- Locates faults along the line for faster line supply recovery time thanks to Travel Wave Form Localization (TWFL) technology.



HIGH VOLTAGE BOOSTER (HVB)

The HVB is directly connected to the catenary system and consists of a single-phase SVC or an MMC-based STATCOM. HVBs inject reactive power to compensate for voltage drops on the line, helping to increase power transfer without the need for additional substations.

The high-voltage booster monitors the catenary voltage and injects reactive power to boost it. This technology is particularly useful for long-distance connections where adding extra intermediate substations is difficult. A typical example is catenaries in tunnels, where boosters can be placed at both ends to maintain voltage and increase traffic capacity.[6]



HVB system

GE Vernova installed four sets of HVBs for SNCF urban rail transportation in France. Due to heavy traffic, significant drops in catenary voltage occurred along the 12 km EOLE tunnel. Two HVBs are positioned at the tunnel entry and two at the exit to compensate for reactive power and maintain voltage stability along the catenary line.

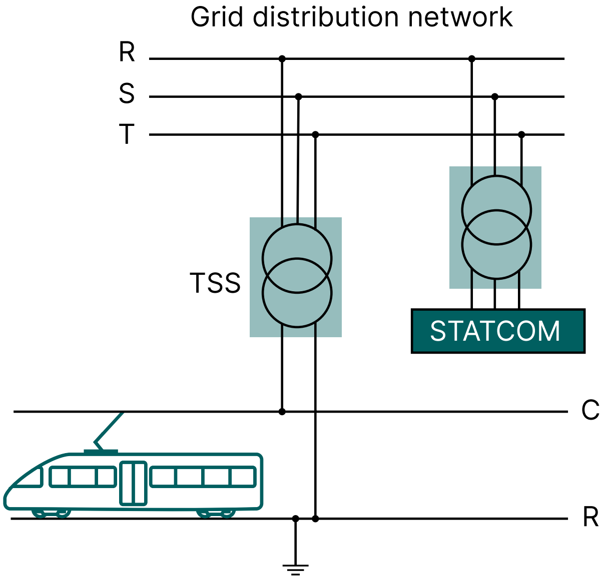
With the widespread adoption of modern rolling stock equipped with power electronics traction systems, catenary grids are more susceptible to instability. The HVB's voltage regulation helps stabilize the catenary grid, ensuring reliable operation.

LOAD BALANCER / STATCOM

Catenaries are powered by single-phase voltage. Traditionally, this single-phase voltage is derived from a three-phase grid using transformers. When the grid is robust, a single-phase transformer can be used by connecting the primary voltage between two phases. For less powerful networks, Scott or LeBlanc transformers are employed[7]. However, in all cases, the voltage and power balance on the grid side is not perfectly managed. To enhance grid voltage balance, load balancers can be utilized.

A load balancer connects to the supply grid and typically includes a three-phase Static VAR Compensator (SVC) or an MMC-based STATCOM. It mitigates negative sequence currents by injecting power between phases to counteract voltage unbalance.

For the Eurotunnel project, which connects France and the UK via a submarine tunnel, Eurotunnel installed a balancer/High Voltage Booster[8]. With nearly 400 trains passing through daily and anticipated traffic growth, Eurotunnel needed to boost the power and stability of its network to maintain a constant flow of traffic and handle peak demands.



STATCOM

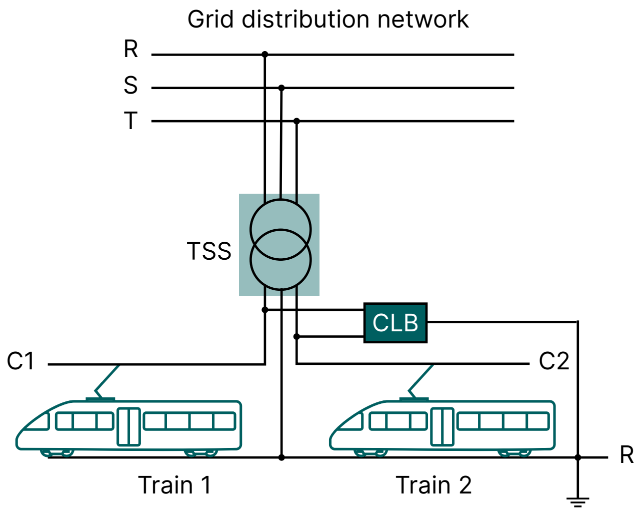
GE Vernova supplied the balancer at the Folkestone Eurotunnel terminal on the English side. This balancer corrects unbalances in the three-phase grid caused by the single-phase catenary supply when the link is powered from the English side and compensates for voltage drops when the link is powered from the French side, acting as a High Voltage Booster in the latter scenario.

CATENARY LOAD BALANCER (CLB)

V/V transformers are another solution for balancing voltage on the three-phase grid and generating two catenary voltages. However, this setup performs best when the loads are evenly distributed between both catenaries. The likelihood of equal power distribution between the two catenary sections is low.

To optimize the performance of this V/V configuration, an RPC (Reactive Power Compensator) can be used to balance the power between the catenaries. The CLB is connected on the catenary side and provides negative sequence correction, harmonic mitigation, and reactive power compensation, while maintaining balanced and sinusoidal currents in the public electrical grid.

Although this configuration is largely theoretical, it could offer several benefits: increasing the distance between substations, reducing catenary losses, optimizing transformer sizing, and improving voltage phase balancing in the grid network with smaller converters.



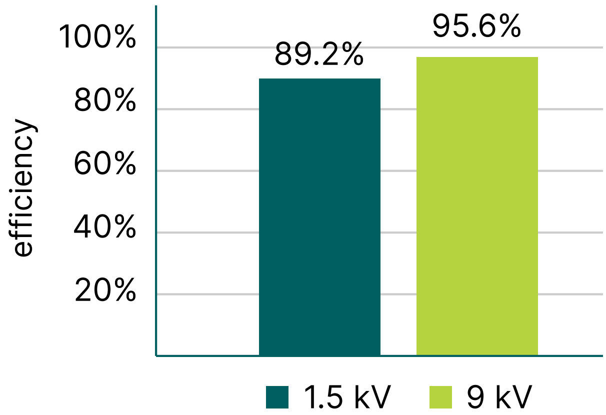
Catenary Load Balancer

DC RAIL

DC Traction power system improvement increasing DC voltage level

DC traction power systems typically operate at 750, 1,500, or 3,000 V. For higher power needs, catenaries are supplied with AC. However, studies are underway to explore the possibility of increasing DC voltage. Raising the voltage from 3 kV to 9 kV could offer several benefits:

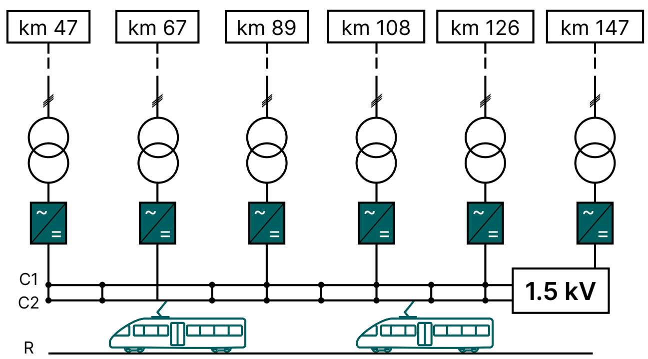
- Reduction in the size of catenary sections and the number of substations,
- Increased efficiency of the traction circuit, potentially saving 5 MWh per day (1.8 GWh per year per 100 km of line),
- Potential application to any 3 kV DC traction power system,
- Gradual, step-by-step improvements.



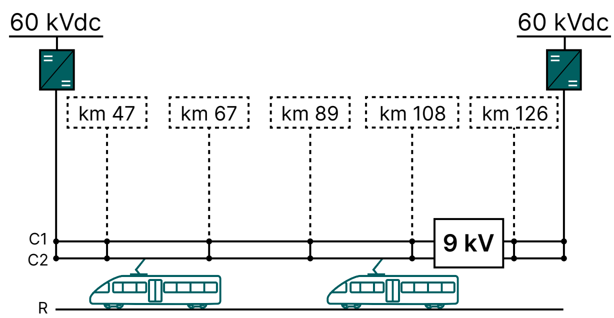
The electricity utility may not allow the recuperated energy from urban railway systems to be fed back into the public grid due to grid stability concerns. These concerns arise from the unpredictable load characteristics of railway systems, as trains require full power only during acceleration, which lasts only a few minutes.

With the anticipated expansion of electric buses in public transport to address air pollution concerns, the issue of load prediction will likely worsen. Fast charging stations, which operate similarly to DC railway substations, will create demand peaks similar to those of railway substations.

The situation becomes even more complex if there is a direct supply of public transport systems by renewable energies. One solution to integrate these challenging loads into the grid is to introduce a Medium Voltage DC (MVDC) ring, creating MVDC energy hubs for mobility. These energy hubs could integrate renewable generation and energy storage.



Conventional DC system



MVDC Traction power supply

GE Vernova's experience has helped to identify the key critical characteristics of applications related to rail power supply:

	SFC	HVB	STATCOM	CLB	MVDC
Power	10-50 MVA (decentralized) 50-150 MVA (centralized)	10-30 MVA	10-80 MVA	10-30 MVA	10-20 MW
Variability power project to project	High variability	High variability	High variability	High variability	Standardized
Catenary Voltage	15 kV 25 KV or +/-25 KV	15 kV 25 KV or +/-25 KV	NA	15 kV 25 KV	9 kV
Catenary transformer	Optional, can work transformer less	Optional, can work transformer less	NA	Optional, can work transformer less	NA
Service criticality	Extremely high (loss of function)	High (degraded mode possible)	Medium (may not affect traffic)	Medium (may not affect traffic)	Extremely high (loss of function)
Opex sensibility to efficiency	High impact	Moderate impact (intermittent operation)	High impact	High impact	High impact
Product longevity	Up to 40 Years	Up to 30 Years	Up to 20 Years	Up to 30 Years	Up to 40 Years

The wide power range allows for a "standard product" approach, where each project configuration is tailored to meet specific requirements. Despite the adaptations, all these rail applications operate within the same power order of magnitude. They typically include a transformer on the catenary side, although this is not necessary when the SFC voltage matches the catenary voltage. These rail applications require high availability (reliability and maintainability), efficiency, and longevity.

MMC TECHNOLOGY

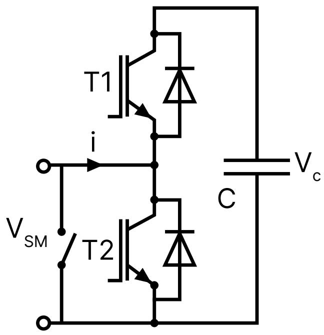
All the different applications described above share the need for a highly flexible and scalable solution combined with a reliable and efficient power electronic system. The Modular Multilevel Converter (MMC) is an optimal solution for meeting the requirements of various rail applications. By nature, an MMC system is modular and scalable, allowing it to adapt to the different voltage and power levels needed for each application.

MMC technology employs different topologies for various applications, but all share a common design: the converter is built from identical building blocks known as submodules.

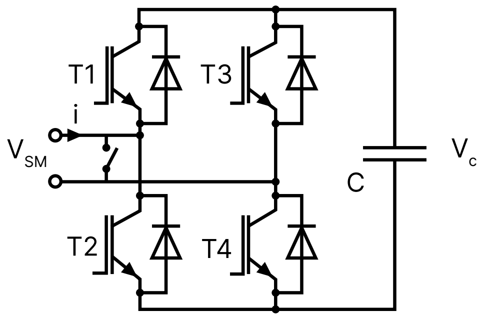
There are two types of submodules available: the half-bridge (HB) and the full-bridge (FB) submodule. An HB module contains only two power semiconductor devices (e.g., IGBTs with integrated diodes) and a capacitor. This design allows the submodule to generate only a positive or zero voltage (Vsm) at the output. The half-bridge module is the simplest submodule in an MMC converter, with the lowest component count.

In contrast, an FB module uses twice as many semiconductors as a half-bridge module. This design enables the submodule to generate both negative and positive voltages (Vsm) at the output. As a result, the module supports the use of simplified and efficient MMC topologies, such as the matrix converter.

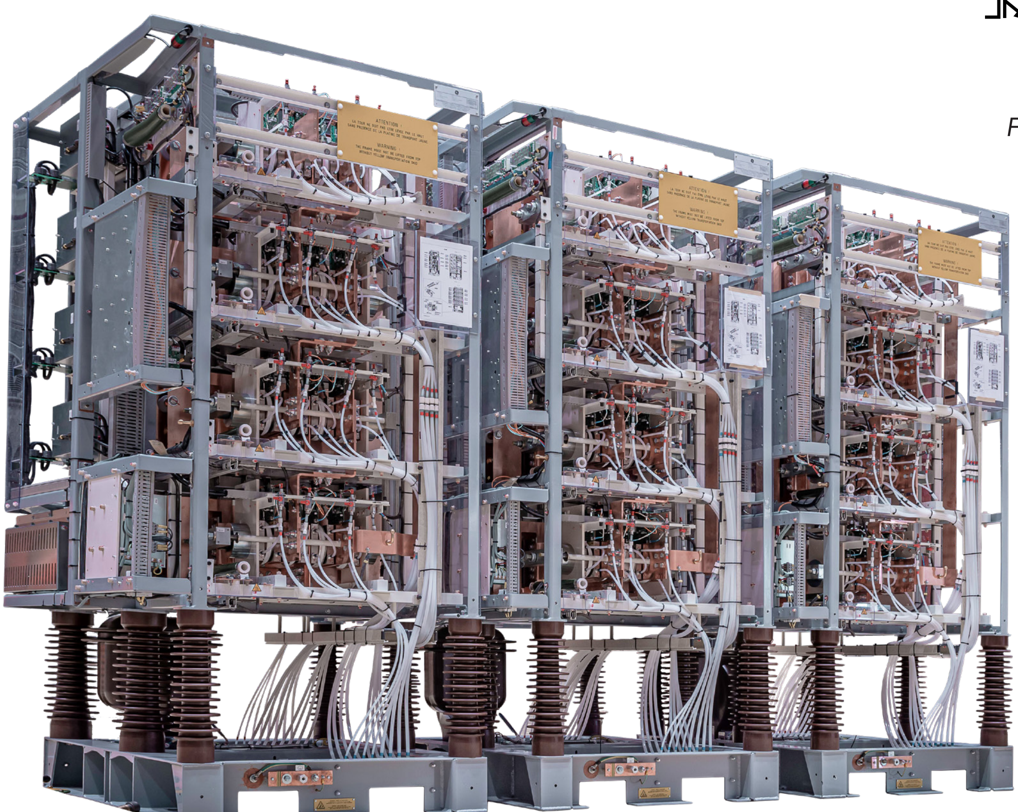
Different MMC topologies are employed depending on the specific function required.



Half-bridge submodule



Full-bridge submodule



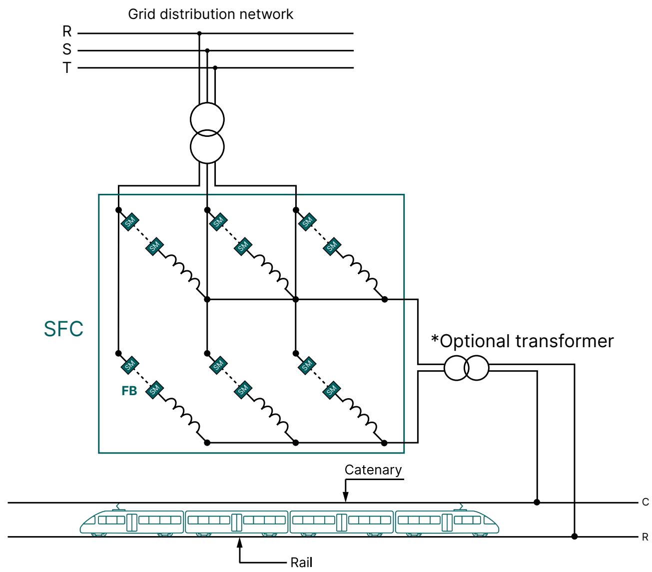
SFC

When the grid frequency significantly differs from the catenary frequency (with at least a 2:1 ratio), the matrix topology, also known as the "Direct SFC topology," is the simplest and most efficient solution. This configuration offers optimal submodule count and includes features such as:

- Direct power supply,
- High Voltage Booster function,
- Transformer/transformer-less options,
- Centralized/decentralized rail supply,
- STATCOM function grid side,
- Simple AC filter on the catenary side (Psophometric filter).

This configuration is suitable for:

- 16.7-25 Hz with single or double, or coaxial feeder,
- 16.7-25 Hz feeder with a boosting transformer,
- 16.7-25 Hz double feeder with autotransformer.



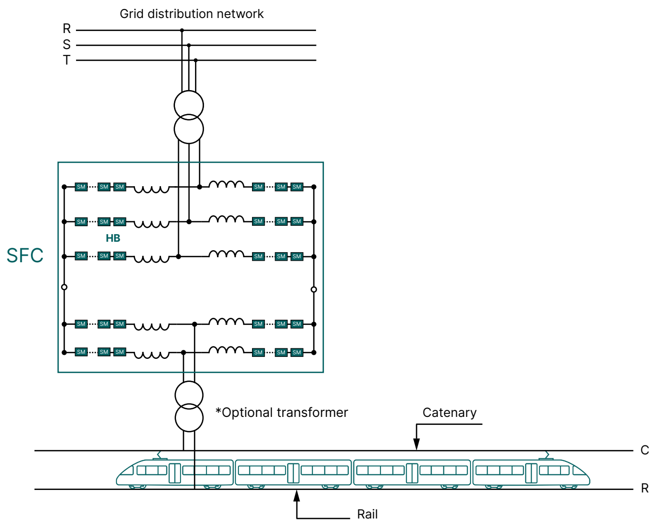
SFC 50-60/16.7-25 Hz with FB modules

An alternative configuration, which can accommodate all catenary frequencies, is indirect conversion. Although this increases the number of submodules compared to the matrix type, the submodules are of the HB type, and the total semiconductor count is slightly lower. This configuration includes features such as:

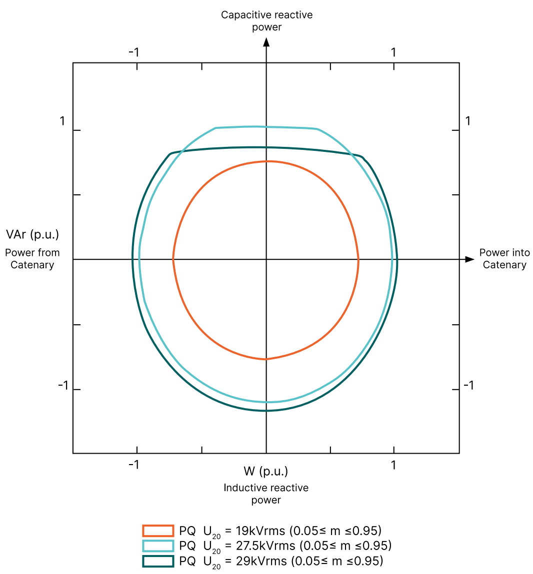
- Indirect power supply,
- Transformer/transformer-less options,
- High Voltage Booster function,
- Pre-charging DC voltage through LV with a rectifier
- AC filter on the catenary side (Psophometric filter),
- Single or double feeder.

This configuration is suitable for:

- 16.7-60 Hz with single or double, or coaxial feeder,
- 16.7-60 Hz feeder with a boosting transformer,
- 16.7-60 Hz double feeder with autotransformer.



SFC 50-60/16.7-60 Hz utilizing HB modules.

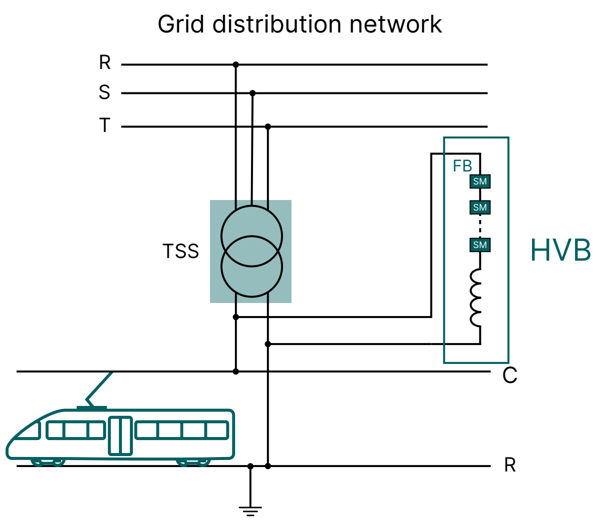


Both topologies enable the full P/Q capability of the SFC station (as shown on the left-hand side). The system can be designed to provide full active and reactive power even if a submodule fails, ensuring full N+1 redundancy. The SFC can operate at any power factor on the railway side, ranging from 0 to +/-1, without any power limitations.

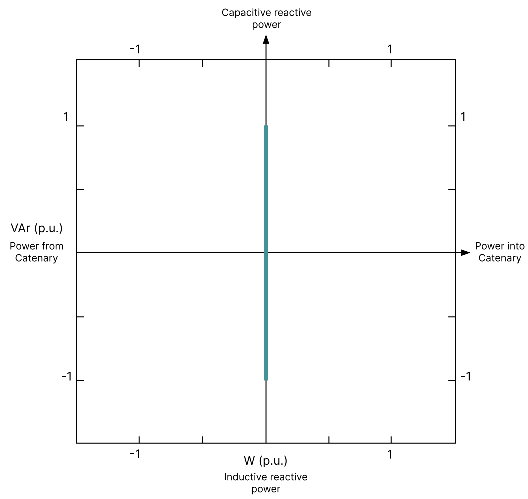
HVB

Voltage support by injecting reactive power into the railway grid can be achieved by implementing a booster. An MMC-based voltage booster, which requires FB modules, is capable of injecting reactive power to support and stabilize the catenary voltage.

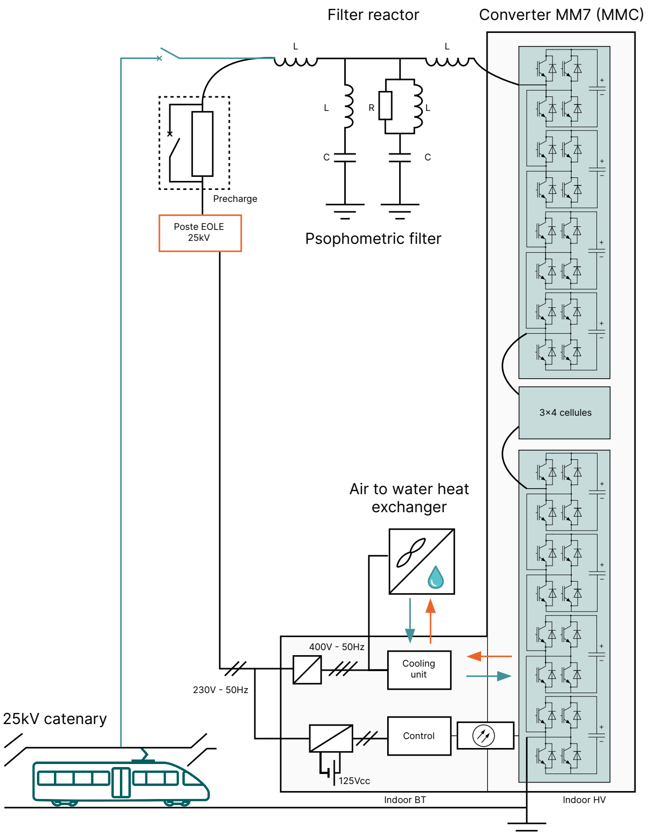
Thanks to the scalability of an MMC, a transformerless connection to the catenary is possible.



Booster with full-bridge modules



The P/Q chart is limited to only inductive or capacitive reactive power injection. No active power can be injected into the catenary.



Typical detailed HVB implementation

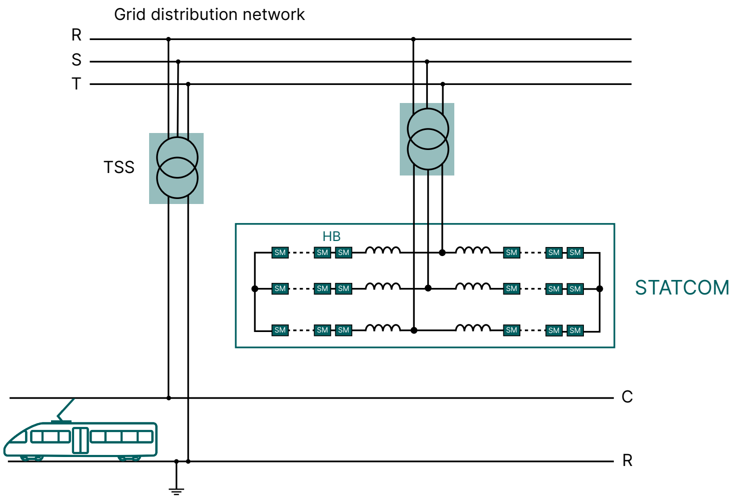
The left picture shows a typical MMC implementation for an HVB. The technology is based on the MM7 model. The converter is constructed by connecting in series five towers, each comprising up to four full-bridge submodules.

The towers are factory-tested for each transport unit. They contain control and protection elements, current and voltage sensors, isolated power supplies, and are pre-assembled on insulators. Each submodule includes four IGBTs and a set of capacitors, functioning as a four-quadrant unit converter.

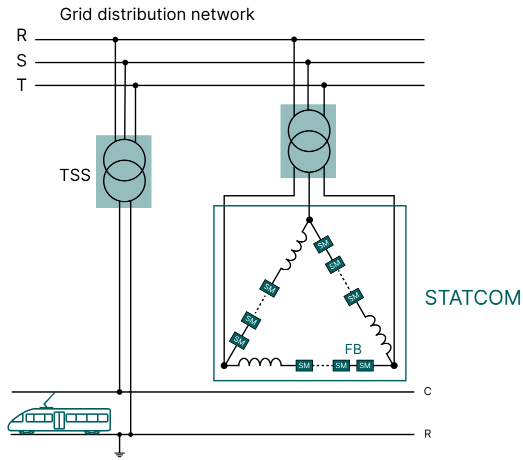
The selection of IGBT type and the minimum number of submodules are determined by voltage and current constraints, as well as the switching frequency required to meet the very stringent harmonic performance standards.

LOAD BALANCER/STATCOM

A load balancer can equalize the load across the three phases. An MMC-based load balancer can use HB modules in a double-star topology or FB modules in a delta configuration.



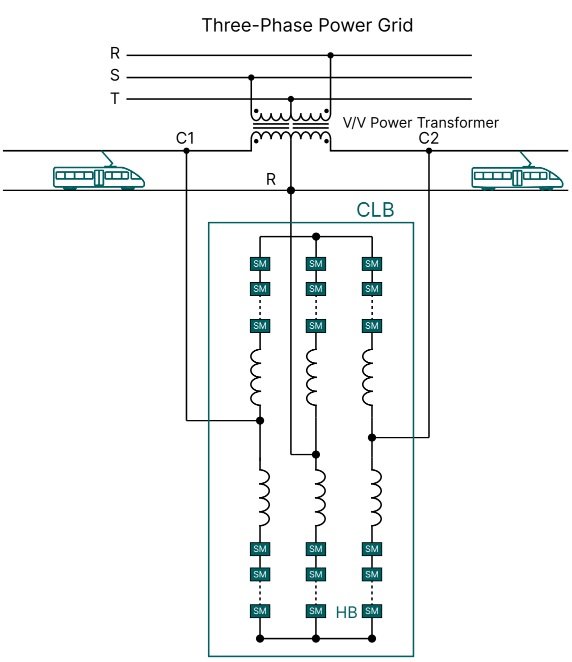
Double-star load balancer with HB modules



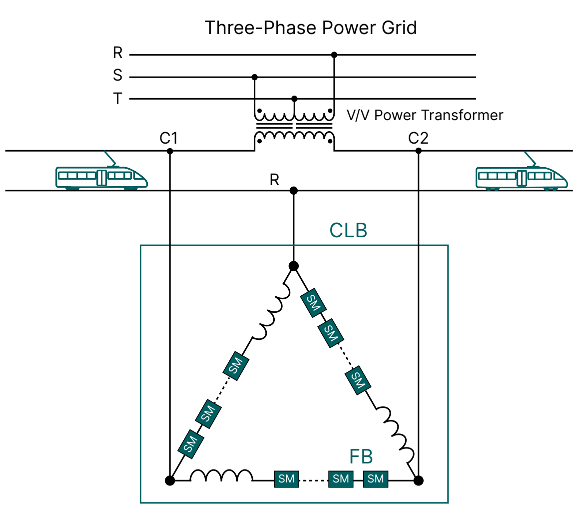
Delta load balancer with FB modules

CATENARY LOAD BALANCER (CLB)

The CLB can be configured with an MMC in a double-star topology, similar to the load balancer topology, using HB submodules. Alternatively, it can also be set up in a delta configuration, using FB modules.



Double-star CLB with HB modules

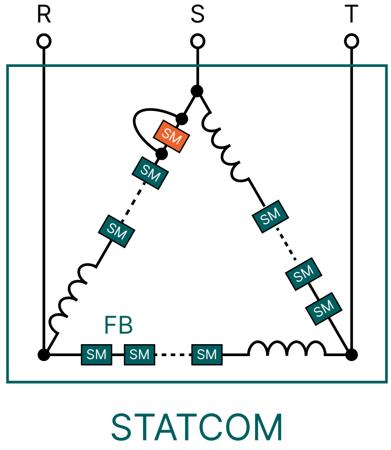


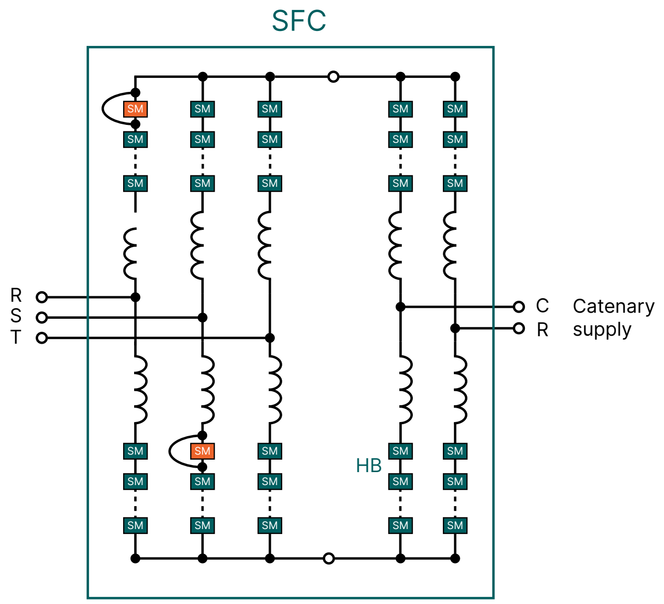
Star CLB with FB modules

SUBMODULES REDUNDANCY

N+1 and N+2 hot redundancy technology helps ensure the system maintains full performance even with one or two component faults, without any power interruption.

This redundancy is managed at the submodule level. Converters are equipped with one or two additional submodules in each arm (serial connection of submodules). If a submodule fails, it is automatically bypassed, allowing the system to continue operating without interruption. This N+1 redundancy covers semiconductor electronic boards and control systems.

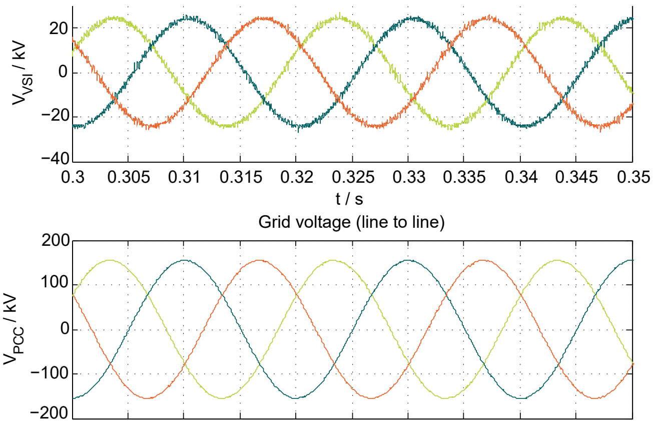




All these topologies use multiple submodules in series (at least 10) to meet the power requirements for rail applications. Adding one extra submodule has only a minor impact on the converter's performance, but it significantly enhances the availability of the converters with minimal cost increase.

HARMONICS

The large number of submodules in series also allows for a smoother output voltage.



The waveform closely resembles a sine wave, with minimal harmonics. This directly facilitates the use of simpler transformers, similar to basic distribution transformers, and simpler harmonic filters.

The more straightforward the transformers and harmonic filters, the better the system's Mean Time Between Failures (MTBF). Large transformers are bulky and heavy, so their failure can significantly impact system availability.

SYNTHESIS

	SFC 50-60/50-60	SFC 50-60/16.7-25	HVB	STATCOM	CLB	MVDC
Submodule type	HB	HB or FB	FB	HB or FB	HB or FB	HB
Topology	Indirect	Matrix (FB) or Indirect (HB)	Catenary inverter single phase	Double Star (HB) or Delta (FB)	Double Star (HB) or Delta (FB)	Double Star
Active power transfer	X	X			X	X
Statcom function grid side	X	X		X		X
Balancing voltage on grid side	X	X		X	X	X
Statcom function catenary side	X	X	X		X	NA
Power range	10-150 MVA	10-150 MVA	10-30 MVA	10-80 MVA	10-30 MVA	10-20 MW
N+1	Yes	Yes	Yes	Yes	Yes	Yes
N+2	option	option	option	option	option	option

CONCLUSION

The MMC offers scalable power with fine granularity due to its unitary submodules[9]. The MM7 topologies, which use standard high-volume submodules, ensure straightforward maintenance. GE Vernova's MM7 MMC topology is an optimal solution for demanding applications.

- **Simpler system solution** compared to Voltage Source Inverters (VSI).
- **N+1/N+2 hot redundancy**, easily integrated into MMC topologies, offering enhanced reliability and availability and allowing substations to operate unmanned and remotely.
- **Modular technology**, allowing reduced maintenance and repair times.
- **High flexibility**, easily adaptable to customer needs, transformer-less or with simple distribution transformers, increasing system availability.
- **Excellent power quality** for both the catenary and grid, including:
  - Harmonics decoupling,
  - Power factor correction,
  - Voltage balance,
  - Energy buffering stored in distributed submodules.

Multilevel converters benefit from GE Vernova's proven power electronics technologies[9]. As a leading player in the industry with strong references in rail, metal, and High Voltage Direct Current applications (HVDC)[10], GE Vernova provides optimized conversion systems tailored to stringent customer requirements and is prepared to offer long-term maintenance throughout the application lifecycle.

References

[1] IEA Article about net zero emission

[2] Decarbonizing transport one of germanys remaining conventional rail lines successfully electrified Station Suedbahn

[3] Railway traction power supply converter station Mannheim

[4] Moreton bay rail link integration of static frequency converters into a metro network

[5] Large-scale electrification of Rail Baltica railway corridor takes shape

[6] GE Power Conversion to provide SNCF Réseau with boosters for future extended RER E line

[7] Power quality phenomena in electrified railways: Conventional and new trends in power quality improvement toward public power systems

[8] Eurotunnel and GE Vernova to Increase Traffic in France/UK Channel Tunnel

[9] MM7 modular multilevel converter brochure

[10] HVDC systems connecting renewable energy and power grids for a sustainable future

SYSTEM SCOPE

PRODUCT DESCRIPTION	GE VERNOVA OFFERING DESCRIPTION
16.7 Hz, 25 Hz HV SFC	MM7 High Voltage converter, direct MMC
50 Hz, 60 Hz HV SFC	MM7 High Voltage converter, indirect MMC
HVB	MM7 High Voltage up to MVAr
STATCOM	MM7 High Voltage up to MVAr
Containerized solution/E house	The static converter installed in existing equipment room or containerized in metallic shelters.
Energy storage	A special storage device and smart control available to provide reliable energy supply when micro cuts occur in shore network, ensuring continuation of the power supply to the ship.
MV/LV switchgear	Wide range of medium and low voltage power distribution equipment and components
Protection & Control devices	Large family of protection & control devices to improve power system safety and ensure efficient recovery.
Visor Connect	Remote connection to equipment, monitoring and support.
ECCS	A powerful SCADA and HMI system comes to synchronise, monitor and control the system.

Glossary of terms

DSO:	Distribution System Operator
FRT:	Fault Ride Through
HVB:	High Voltage Boosters
HVDC:	High Voltage Direct Current
IEGT:	Injection Enhanced Gate Transistor
MMC:	Modular Multilevel Converter
NZE:	Net Zero Emissions by 2050 Scenario
OPEX:	OPerational EXpenditure
SFC:	Static Frequency Converter
SVC:	Static VAR Compensator
VSI:	Voltage Source Inverter
RPC:	Rail Power Conditioner
CLB:	Catenary Load Balancer
MTBF:	Main Time Between Failure
PIBe:	Power Interface Board based on Ethernet
ECCS	Energy Control & Command System

About Power Conversion, a GE Vernova business

We apply the science and systems of power conversion to help drive the electric transformation of the world's energy infrastructure. Designing and delivering advanced motor, drive and control technologies that help improve the efficiency and decarbonization of energy-intense processes and systems, helping to accelerate the energy transition across marine, energy and industrial applications.
We are at the heart of electrifying tomorrow's energy.