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Railway Electric Power Feeding Systems

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Introduction

Electric power technology in the railway industry refers to the means of supplying good-quality electric power to the electric motors. It primarily consists of power conversion technology at sub-stations, feeding circuits for DC and AC feeding systems, and the structure, materials, measurement, and maintenance of the electric overhead lines.

Power collection via the overhead line and pantograph, introduced nearly 100 years ago early in the history of electric railways, remains basically unchanged in physical appearance. However, technological developments during the past century have done much to greatly increase the current capacity, speed, and safety. Today, the capacity is more than sufficient to drive modern super high-speed trains. This article discusses all aspects of electric power supply systems for railways, ranging from the history of electrification of Japanese railways to today's sophisticated power supply facilities. It also compares them with their counterparts in other countries.

World Railway Electrification Systems

Table 1 shows various feeding systems around the world and the electrification distances.

The history of electric railways dates back to 1835 when T. Davenport fabricated a model electric car powered by voltaic cells and put it on public exhibition. The first practical electric cars debuted in 1879 when a 150-V dc, 2.2-kW, bipolar motor pulled three passenger cars at a maximum speed of 12 km/h at the Trades Exhibition in Berlin. In 1881, Siemens Halske built the world's first electric railway in Lichterfelde marking the first passenger electric railway.

Electric operation is often preferred on railways with many long tunnels or on underground railways because the energy efficiency is higher than steam or diesel locomotives and does not involve on-board combustion. The high tractive force also makes electric operation suitable for lines running through hilly regions. As a consequence, electric train operation made remarkable progress. It started first with direct-current feeding systems capable of driving a DC motor directly and offering high tractive force and easy speed control.

Although a 3000-V dc feeding system is widely used in many other countries, some Japanese railways using DC rely on a 1500-V dc system.

The other alternating-current feeding system originated in Europe using a single-phase, commutator-type motor. Special low frequencies such as 25 Hz and 16.66 Hz were introduced in Austria, Germany, and other countries to minimize rectification failures. Later advances in silicon commutator technology paved the way for AC feeding systems using commercial frequencies in France and elsewhere. The 25-kV system is used widely around the world while Japan relies on a 25 kV system for shinkansen and a 20-kV ac feeding system for 'conventional' railways. (In this article, 'conventional' means all JNR/JR narrow-gauge lines, all non-JR railways, and the Akita and Yamagata shinkansen, which were converted to standard gauge from narrow gauge.)

The three-phase, alternating-current feeding system is used with induction motors in Europe for railways with steep mountain grades, while a 600-V system, featuring speed control by a power converter, is used in Japan for new urban transit systems.

Table 1 World Electric Railway Feeding Systems and Electrified Distances (1996)

System Type			Japan[1] km	Japan[1] %	World (including Japan) km	World (including Japan) %	Main Countries
DC	Less than 1,500 V		915	5	5,106	2	Germany, UK, Switzerland, USA
	1,500 V to 3,000 V (Mostly 1,500 V)		10,484	61	22,138	9	France, Spain, Netherlands, Australia
	3,000 V or more (Mostly 3,000 V)				78,276	33	Russia, Poland, Italy, Spain, South Africa
Single-phase AC	50 Hz • 60 Hz	Less than 20 kV			245	0	France, USA
		20 kV	3,741	22	3,741	2	
		25 kV	2,037	12	84,376	36	Russia, France, Romania, India, China
		50 kV			1,173	0	USA, Canada, South Africa
	25 Hz • 11 kV to 13 kV				1,469	1	USA, Austria, Norway
	16.66 Hz	11 kV			120	0	Switzerland
		15 kV			35,461	15	Germany, Sweden, Switzerland
Three-phase AC			30	0	43	0	Switzerland, France
Unknown					3,668	2	Kazakhstan[2], France
Total			17,207	100	235,816	100	

Notes: [1] Statistics include Japanese subways and AGTs.
[2] Kazakhstan is 3,528 km (3,000 V dc and 50 Hz 25 kV ac) but details are not known.

Sources: (1) Railway Electrical Engineering Association of Japan, vol.8, no.10, pp.3–5, Oct. 1997
(2) Ibid., vol.8, no.11, pp. 77–78 and pp. 81–83, Nov. 1997

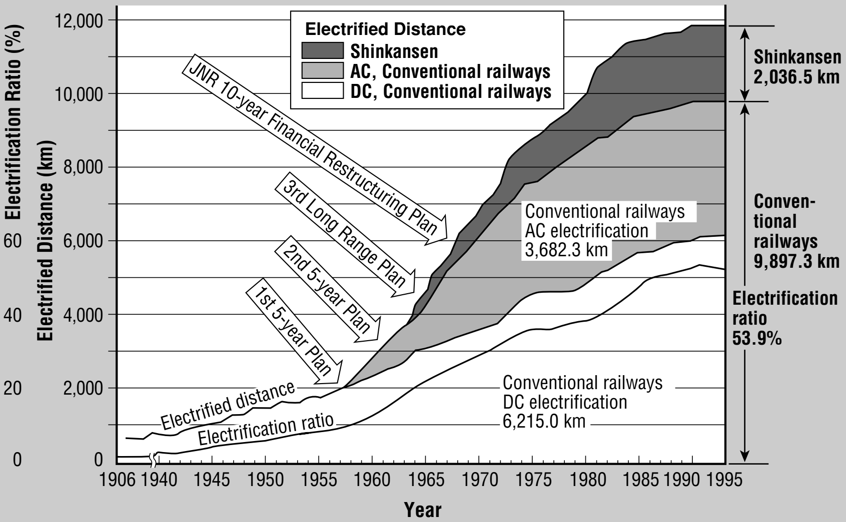
History of Railway Electrification in Japan

Commercial operation of electric railways in Japan dates back to 1895 when a 500-V dc tram system was started in Kyoto. The first electric railway owned by the Japanese Government Railways began operation in 1906 between Ochanomizu and Nakano in Tokyo, which used to belong to Kobu Railways before being purchased by the government. The 600-V dc system was later replaced by a 1200-V dc system to prevent voltage drop. In 1922, it was replaced again by a 1500-V dc system when the section between Yokohama and Kozu was electrified. The 1500-V dc system is still used today by all DC electric railways in Japan.

The postwar increase in transportation demand in Japan led to the introduction of more powerful electric locomotives around 1950. At that time, it was feared that the 1500-V dc system had reached its limit, and a study was started on railway electrification based on commercial-frequency, single-phase alternating current. After a successful demonstration test on the Senzan Line, the first commercial operation using an electric locomotive started in 1957 on the Senzan and Hokuriku Lines, soon followed by a 20-kV single-phase, alternating-current system using a step up or boosting transformer (BT) to minimize inductive interference in telecommunication lines.

In 1964, the Tokaido Shinkansen began operations using the BT feeding system, marking the first high-speed train operation with a maximum speed of 210 km/h. However, it soon faced maintenance and other technical problems associated with the large collection current requiring complex anti-arcing designs. This led to a study of the auto transformer (AT) feeding system, which was introduced on the Yatsushiro-Nishi Kagoshima section of the Kagoshima Line in 1970, and on the Shin Osaka–Okayama section of the Sanyo Shinkansen in 1972. Today, the AT feeding system is the standard for all AC electric railways in Japan.

Figure 1 History of Railway Electrification in Japan*



Note:
* Including Japanese Government Railways, Japanese National Railways (JNR, from June 1949 to March 1987) and JRs, but excluding private railways

Figure 1 shows the history of railway electrification in Japan from the era of the Japanese Government Railways until the present JRs. Figure 2 maps the various systems in Japan. Roughly speaking, the 1500-V dc system is used on the conventional railways in Honshu (Kanto, Tokai, Kansai, and Chugoku districts) and Shikoku, while the 20-kV ac system is mainly used in Hokkaido, northern Honshu (Tohoku and Hokuriku districts), and Kyushu. All shinkansen use the 25-kV ac system. In contrast, most private railways rely on the 1500-V dc system, while the 600- or 750-V dc system is used by subways and some other railways.

Various Feeding Systems

From power station to railway sub-station

The electric power generated by power stations is carried to electric railway sub-stations by transmission lines. JR East has its own hydroelectric power station in Niigata Prefecture (on the Shinano River) as well as a thermal power station in Kawasaki City in Kanagawa Prefecture. These two power stations supply the railways in the Tokyo metropolitan area.

In Japan, the receiving voltage at sub-stations for direct-current electric railways is usually extra-high tension at 22, 66, or 77 kV. This is converted to 1200 V by a transformer, and then to direct current by a rectifier at the rated voltage of 1500 V (no-load voltage of 1620 V). Subways and some private railways use 600 or 750 V dc.

The receiving voltage for alternating-current conventional electric railways is an extra-high voltage of 66, 77, 110, or 154 kV. The shinkansen use receiving voltages of 77, 154, 220, or 275 kV. The conventional railways use a feeding voltage of 20 kV, and the shinkansen use single-phase at 25 kV.

Figure 2 Map of Railway Electrification of JR Group in Japan

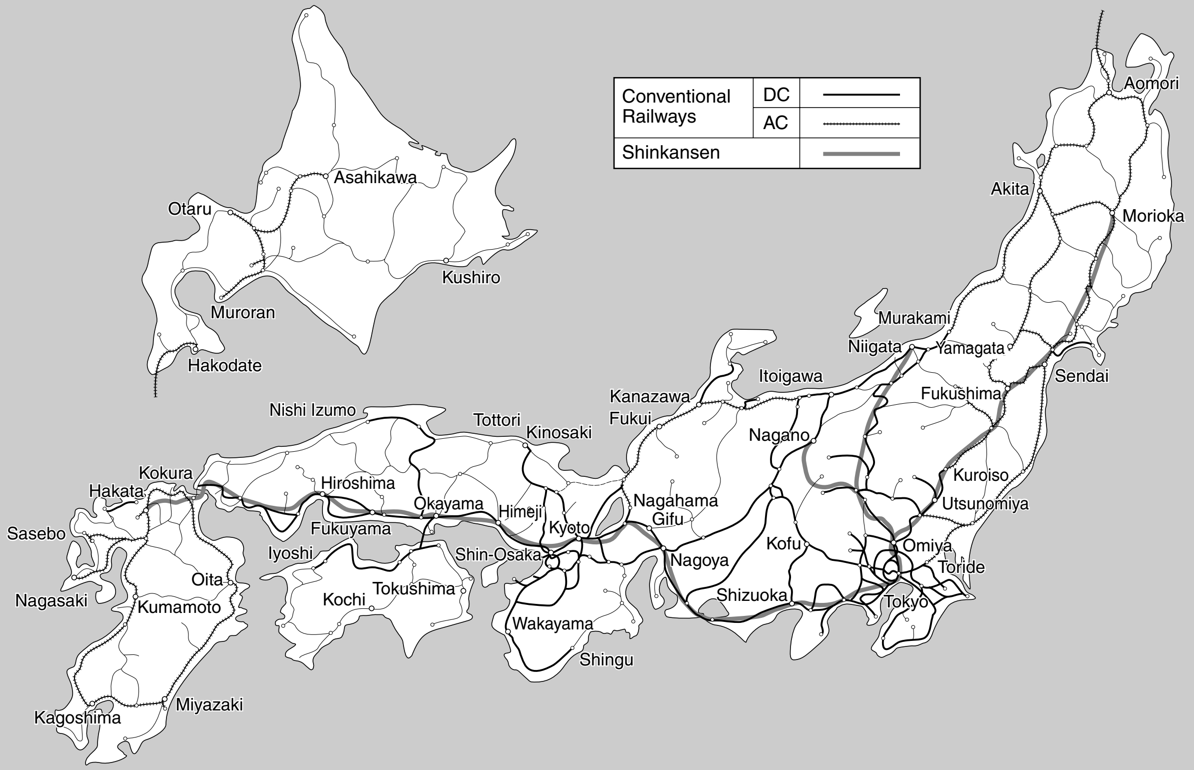
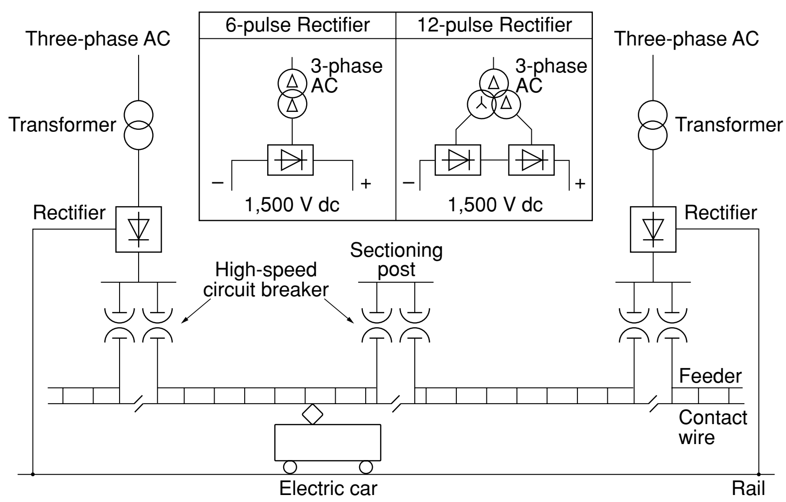


Figure 3 Structure of a DC Feeding System



DC feeding system

A direct-current feeding system features a three-phase bridged silicon rectifier for conversion from alternating to direct current. Since the three-phase rectifier uses a 6-pulse system, it causes lower harmonics in the AC side and distortion in the voltage waveform, lowering the power quality. To reduce the harmonics, a more-modern rectifier design using a 12-pulse system featuring two sets of 6-pulse rectifying circuits, with AC input voltage phases 30° apart, connected in series or parallel, is used. Figure 3 is an example showing the structure of a DC feeding circuit connected to the nearest sub-station. Section and tie posts are sometimes used to prevent voltage drops on double tracks where sub-stations are located far apart. In this case, the up and down tracks are connected by a high-speed circuit breaker. The distance between sub-stations is about 5 km on metropolitan trunk lines and 10 km on other lines.

Efforts are being made to introduce regenerative cars on DC electric railways in order to reduce the weight and save energy. They are designed to convert the kinetic energy into electric power during deceleration and return it to the overhead lines. However, the regenerated power would be wasted if there are no cars in the section to use it. This loss can be prevented by thyristor rectifiers, thyristor inverters, thyristor chopper resistors, or simultaneous up and down track feeding systems. Such devices are used on some sections; Figure 4 shows an example of a thyristor inverter. In this system, the motive power is supplied from a rectifier, and when the regenerative power exceeds the motive power requirement, the inverter is activated automatically to supply power to stations, etc.

AC feeding system

Since three-phase power from the power utility is converted to two single phases, to ensure that the current is as close as possible to the three lines of the three-phase side, one separate phase is fed to each of the overhead up and down tracks. Various methods can be used to connect the feeding transformers. Today, the Scott connected transformer (Fig. 5) is used to receive extra-high tension, and the modified wood-bridge connected transformer (Fig. 6) is used to receive extra-high voltage, with the neutral point directly grounded.

Figure 7 shows the composition of an AC feeding circuit. It includes feeding AC sub-stations, sectioning posts for feed sectioning, and sub-sectioning posts for limited sectioning, all located along the tracks. The feeding sub-stations feed the two single phases converted from the three-phase source by a feeding transformer in the opposite track directions,

Figure 4 Power Regeneration by Thyristor Inverter

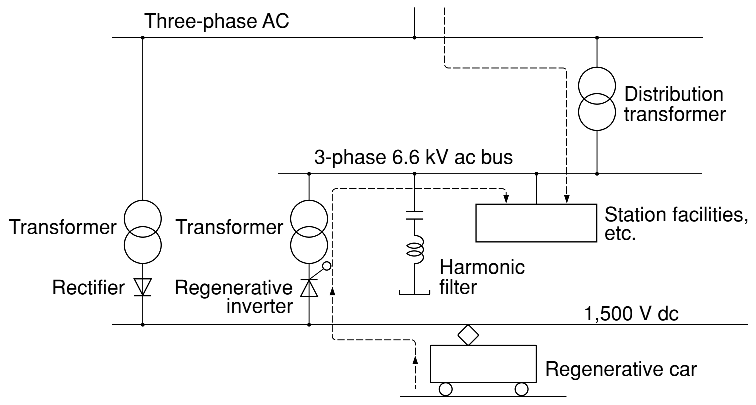


Figure 5 Scott Connected Transformer

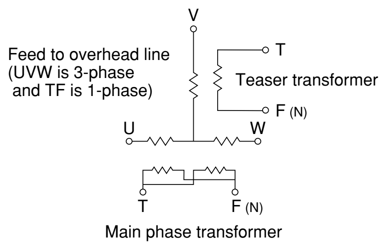


Figure 6 Modified Wood-bridge Connected Transformer

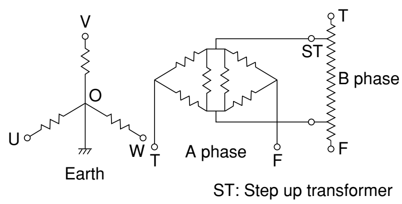


Figure 7 Structure of an AC Feeding System

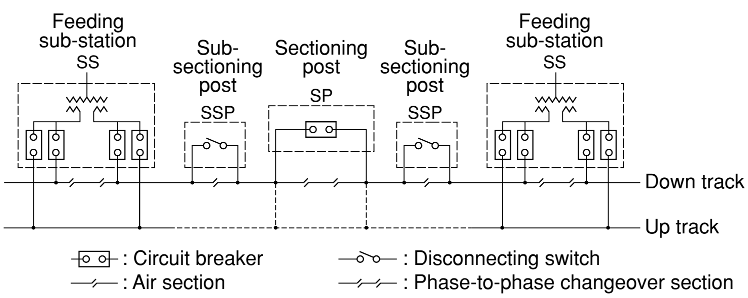


Table 2 Feeding Voltages and Distances between Sub-stations of Various AC Feeder Systems in Japan

Feeding system	Feeding voltage (kV)		Distance between sub-stations (km)	
	Conventional railways	Shinkansen	Conventional railways	Shinkansen
BT	22	—	30 to 50	—
AT	44	60	90 to 110	20 to 60
Coaxial	—	30	—	10

with a 90° phase offset.
Table 2 shows the feeding voltages and the distances between sub-stations of various AC feeding systems in Japan.

BT feeding system

Figure 8 shows the composition of a BT feeding circuit. A BT is installed every 4 km on the contact wire to boost the return circuit current on the negative line. This design minimizes the inductive interference on telecommunication lines because the current flows to the rail only in limited sections.
In particular, when an electric car passes a BT section, a large arc is generated in the section, and a large load current can cause a very large arc that can damage the overhead line. Consequently, capacitors are often inserted serially in the negative feeder to compensate for the reactance and reduce the amount of current intercepted by the pantograph, thereby reducing arcing, and also helping to prevent voltage drop.

Figure 8 Structure of NF-based BT Feeding System

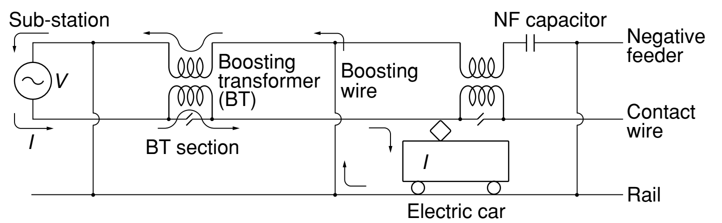
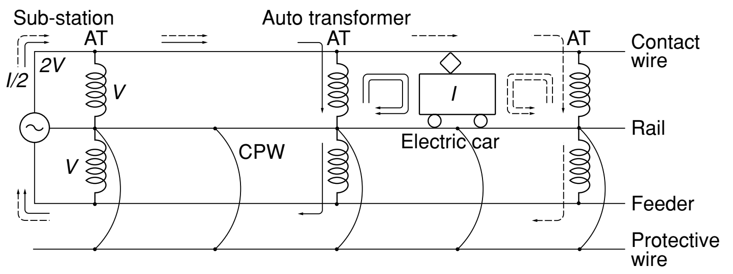


Figure 9 Structure of AT Feeding System

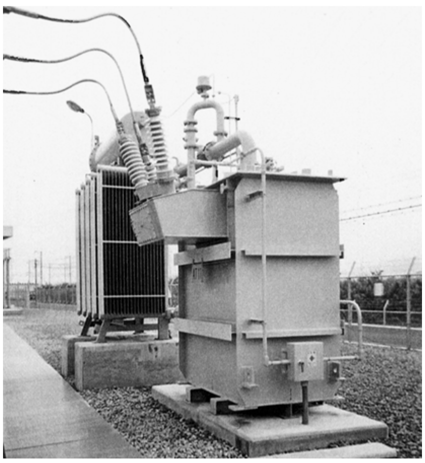


AT feeding system

In the AT feeding system, the feeding voltage of the sub-station is twice the voltage supplied to the electric car. An AT, at every 10 km along the track, cuts the voltage to the overhead-line voltage as necessary. This is very effective in reducing inductive interference in telecommunications lines. Figure 9 shows the composition of an AT feeding system, and the photograph below shows an external view of an AT designed for shinkansen.
In Japan, the AT is designed with a turn ratio of 1:1 and the sub-station feeding voltage is twice the overhead-line voltage. This system is ideal for high-speed and large-capacity electric cars because there are no large voltage drops nor arcing sections.

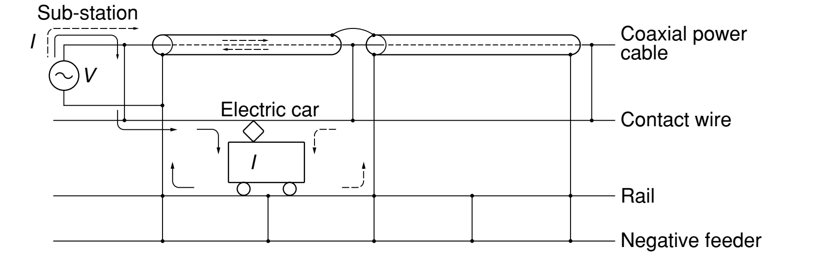
Coaxial cable feeding system

As shown in Figure 10, the coaxial cable feeding system features a coaxial cable laid along the track. Every several kilometers, the inner conductor is connected to the contact wire and the outer conductor is connected to the rail. The cable itself is very expensive but the conductor



External view of AT (60/30 kV, 7500 kVA) *(RTRI)*

Figure 10 Coaxial Cable Feeding System



layout is simple, making it ideal for use where space is limited. Japan is the only country that uses this system (the Tokyo sections of the Tohoku Shinkansen and Tokaido Shinkansen).

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

Detecting Feeding Faults

Feeding circuit faults can be caused by electric car faults, overhead line faults, flying objects, and animals (birds, snakes, etc.). The high voltage causes a high fault current and, consequently, a protective relay is used to instantly detect any fault and trip a power circuit breaker.

DC feeding system

In a DC feeding system, typically, the current for the electric car increases smoothly, but a fault current always increases abruptly. A ΔI-type fault selective relay at sub-stations is used to detect faults based on this difference.

AC feeding system

In an AC feeding system, faults are detected by a combination of a distance relay and an AC ΔI-type fault selective relay (Figure 11). The distance relay monitors the overhead line impedance from the sub-station and recognizes an event as a fault when the impedance falls within a predetermined rectangle on the impedance plane. As with DC systems, the AC ΔI-type fault selective relay detects the change in current.

Furthermore, locators are used to mark fault points based on the current distribution, so any fault can be corrected promptly.

Overhead Line Systems

Catenary system

An electric railway takes its power for the electric motors, lights, air conditioning, etc., from the overhead line using the pantograph on the roof.

The pantograph is in constant contact with the overhead line (contact wire) located about 5 m above the rails, whether the train is moving or not. Therefore, the overhead line must always be located within the pantograph range, and the pantograph must always maintain contact with the overhead line to supply uninterrupted, good-quality power at all times. To meet these requirements, the overhead equipment is generally designed bearing the following in mind:

- Must have characteristics meeting train speed and current requirements
- Must be at uniform height above rail to optimize pantograph power collecting characteristics, so entire equipment must have uniform spring constant and bending rigidity
- Must have minimum vibration and

Figure 11 Protective Zone of AC Electric Railway Protective Relay

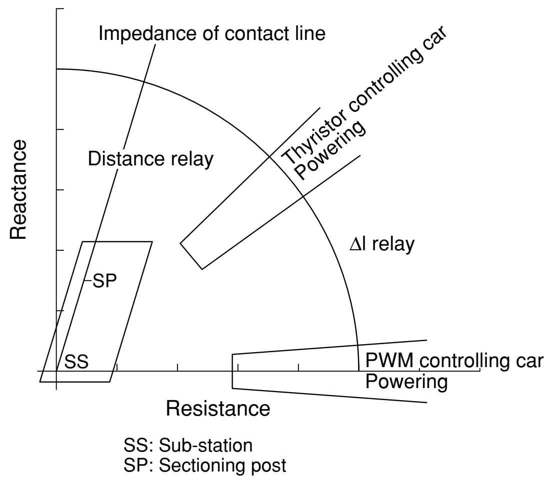


Figure 12 Overhead Lines of World High-Speed Railways

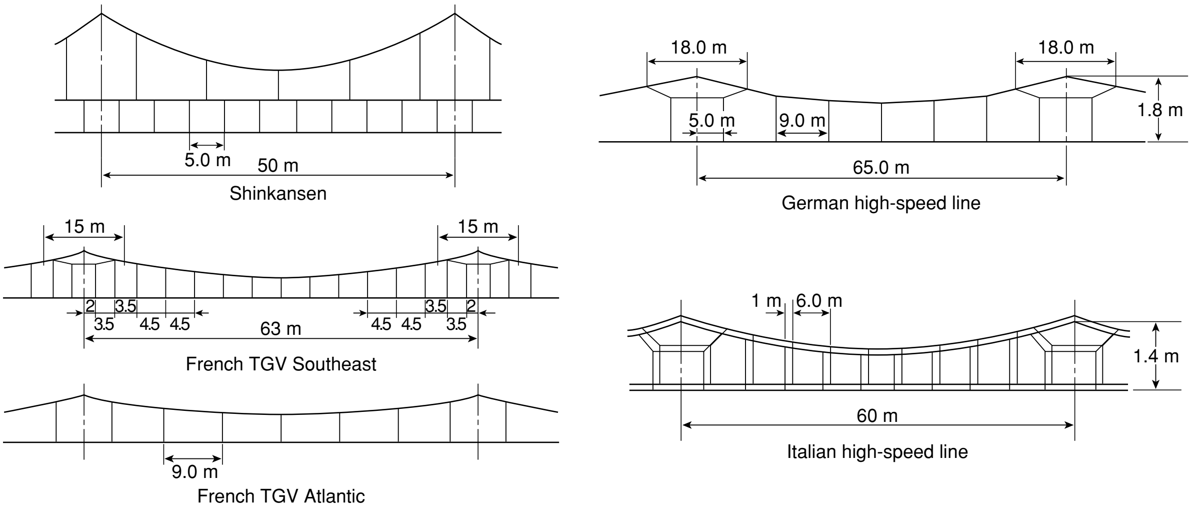


Table 3 Comparison of Overhead Line Constants on Dedicated High-speed Lines

Item		Japan	France		Germany	Italy
			TGV Southeast	TGV Atlantic		
Catenary type		Heavy compound type	Stitched and simple	Simple	Stitched and simple	Twin stitched and simple
Standard span [m]		50	63 (Stitched wire 15)	63	65 (Stitched wire 18)	60 (Stitched wire 14)
Standard wire height [m]		5.0	4.95	4.95	5.3	4.85
System height [mm]		1,500	1,400	1,400	1,800	1,400
Wire grade	Suspended	St 180 mm^2 (1.450 kg/m)	Bz 65 mm^2 (0.59 kg/m)	Bz 65 mm^2 (0.59 kg/m)	Bz11 70 mm^2 (0.63 kg/m)	CdCu 153.7 mm^2 (1.42 kg/m)
	Auxiliary suspended	Cu 150 mm^2 (1.375 kg/m)	Bz 35 mm^2	—	Bz11 35 mm^2 (0.31 kg/m)	(0.30 kg/m)
	Contact wire	Cu 170 mm^2 (1.511 kg/m)	CdCu 120 mm^2	Cu 150 mm^2 (1.33 kg/m)	CuAg Ri 120 mm^2 (1.08 kg/m)	CuAg 151.7 mm^2 (1.35 kg/m)
Contact line total density [kg/m]		4.34	1.65	1.92	1.71	2.77 × 2
Catenary wire tension	Suspended [N]	24,500	14,000	14,000	15,000	18,400
	Auxiliary suspended [N]	14,700	4,000 (Stitched wire)	—	2,800 (Stitched wire)	2,900 (Stitched wire)
	Contact wire [N]	14,700	14,000	20,000	15,000	14,700
	(Total tension) [N]	(53,900)	(28,000)	(34,000)	(30,000)	(33,100 × 2)
Wave propagation velocity of contact wire [km/h]		355	414	441	424	376
β (train speed/ wave propagation velocity)		0.68, 0.76 (= 240, 270/355)	0.65 (= 270/414)	0.68 (= 300/441)	0.59 (=250/424)	0.66 (= 250/376)
Pre-sag		None	1/1,000	1/1,000	1/1,000	1/1,000

motion to ensure smooth pantograph passage during high-speed operation or strong winds
- Must have strength to withstand vibration, corrosion, heat, etc., while maintaining balance with reliability and operating life span

Figure 12 compares the catenary equipment for high-speed trains in different countries. In Japan, compound catenary equipment consisting of three longitudinal wires is used for shinkansen, while simple or stitched catenary equipment is used in Europe. The Italian high-speed line uses twin catenary equipment to supply the large current for the 3-kV dc electrification. Table 3 compares the constants of these various catenary systems.

Compound catenary systems feature less pantograph vertical motion and larger current capacity but require a larger number of components resulting in a more complex design.

In Europe, pre-sag is often used to compensate for the large vertical motion of the pantograph in the simple catenary system. Pre-sag refers to a special design feature in which the height of the contact wire is lower at the centre of the span by an amount equal to around 1/1000 of the span. In real terms, generally, the contact wire height is 20 or 30 mm lower than the supports at the centre of the span, thereby suppressing the pantograph vertical motion. This design is effective for the overhead lines on the French and German high-speed lines which have a large amplitude, but is less effective for overhead lines with small amplitudes like the shinkansen and the Italian high-speed line.

Lateral wave propagation

The most critical constants for the mechanical performance of the overhead line are the weight and tension per unit length. The total tension is relative to the push-up force of the pantograph and is closely related to the vertical motion of the overhead line. It is 54 kN for shinkansen and 28 to 34 kN for the French and German systems. The Italian system has a total tension of 66 kN because it uses a twin catenary system with a larger wire size. The pantograph push-up force is roughly 70 to 80 N for Japan, 130 to 250 N for France and Germany, and 200 to 300 N for Italy. This means France and Germany have an overhead line amplitude about four times greater than that of Japan. Generally speaking, greater stability results from smaller overhead line amplitude. It also reduces the fault frequency and damage to components. The French and German systems seem to allow larger amplitudes at the cost of fewer pantographs.

The square root of the ratio of the contact wire tension to the weight per unit length represents the velocity of the lateral wave propagating along the wire. This is the most important parameter in overhead line design. In railway technology, this velocity is called the wave propagation velocity and is recognized as the critical speed.

Table 3 shows the wave propagation velocity and the ratio of the train speed to the wave propagation velocity (β). Simulation and experiments have verified that as the train speed approaches the wave propagation velocity, the overhead line amplitude and local bending increase, making it harder to maintain contact between the pantograph and overhead line. It is estimated that the resulting performance drop becomes apparent when the train speed exceeds 70% to 80% of the propagation velocity. At this speed, loss of contact with the line increases greatly, and in extreme cases, the overhead line itself can be destroyed.

Consequently, the contact wire constant must be set so that the propagation velocity is significantly faster than the train speed. The propagation velocity can be increased by laying a lighter wire at a higher tension. In the case of a pure copper contact wire, after considering safety factors, the maximum achievable speed (neglecting wear) is around 500 km/h. Any further increase in the wave propagation velocity can only be achieved by using wires with a higher tensile resistance per weight unit length. In Japan, wires in use or under development include copper alloys, and other alloys, as well as compound wires such as aluminium-clad steel wire, and copper-clad steel wires.

In Table 3, the β values are all 0.7 or lower, indicating that all countries have selected values within the above-mentioned stable velocity range for train speeds.

The photograph (above left) shows a heavy compound overhead line. The Nagano-bound Shinkansen (Takasaki–Nagano section), which started operations in October

Heavy compound overhead line of Tohoku Shinkansen (RTRI)

Simple catenary equipment of Nagano-bound shinkansen (RTRI)

Figure 13 Third Rail Arrangement

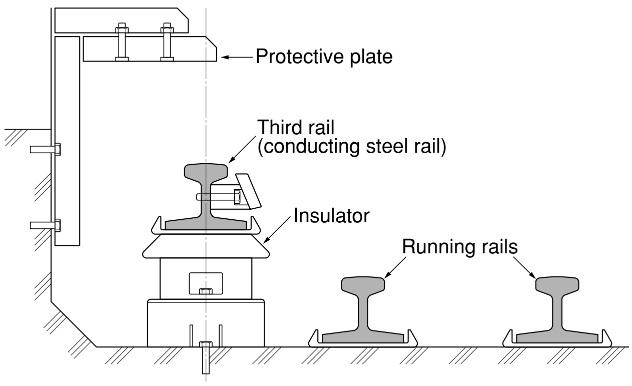
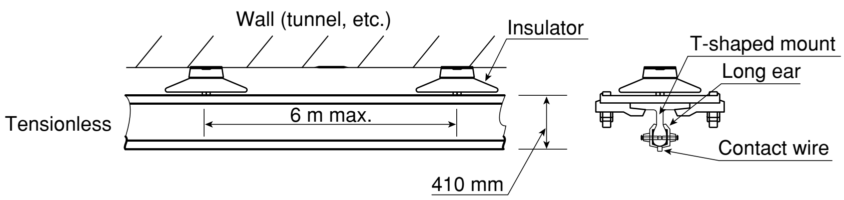
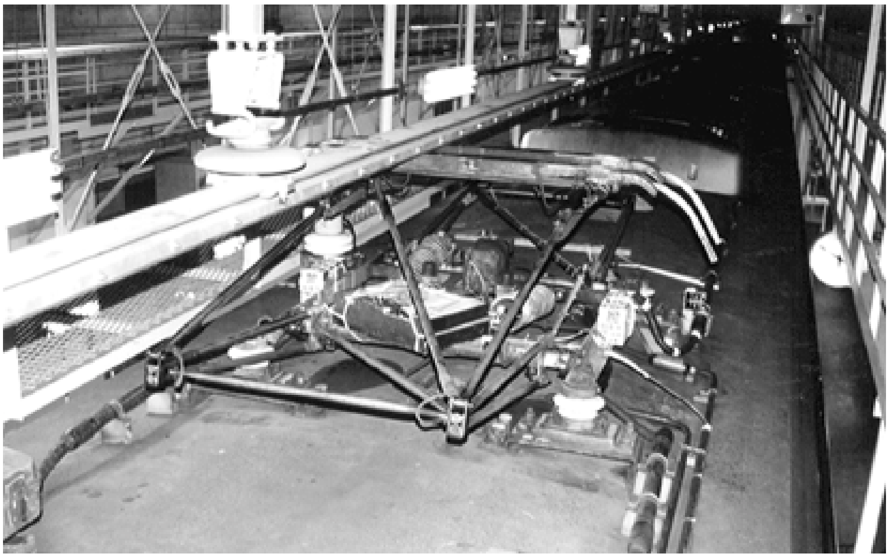


Figure 14 Overhead Rigid Conductor System





Overhead rigid conductor system and pantograph *(RTRI)*

1997, uses the simple catenary overhead equipment found commonly in Europe. This system was chosen for economy because the less-frequent train operation consumes only a small proportion of the current-carrying capacity. This shinkansen uses a 110-mm^2 copper-clad steel wire (Fig. 15b) with a tension of 20 kN to withstand the train operating speed of 260 km/h. This is the first simple catenary system for high-speed operation in Japan.

Third-rail conductor

In the third-rail conductor system, the collector is laid next to the rail to save space in restricted subways. This system dates back nearly 70 years to 1927 when it was first introduced on the Ginza Line of the Tokyo Rapid Transit Authority (TRTA). The voltage is 600 or 750 V. Figure 13 shows the structure. In Japanese subway systems, it is shielded at the top and on one side for safety; a flat shoe collects current directly from the top of the rail, which is supported by insulators every 2.5 to 5 m. This third rail system is limited to a maximum speed of around 70 km/h due primarily to the underground conditions in the Tokyo metropolitan area. However, experiments show it is capable of serving speeds exceeding 100 km/h.

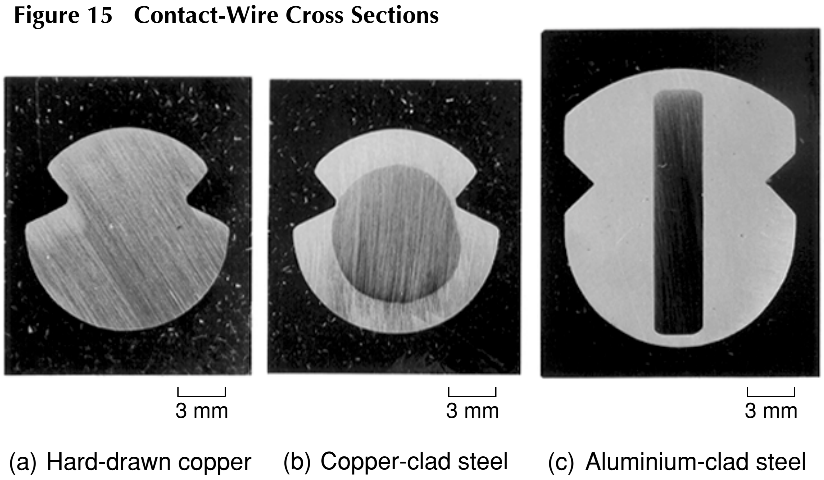
Overhead rigid conductor system

The overhead rigid conductor system has been developed as an overhead line for direct links between subways and suburban railways. It features toughness and small space requirements (Fig. 14 and opposite photograph) and prevents broken wires and other accidents, especially in the subway sections.

The maximum speed has been limited to 90 km/h primarily due to the short distances between stations and frequent curves in the metropolitan subways.

The system runs at a voltage of 1.5 kV to allow direct connections to suburban railway systems. It has been used for nearly 40 years on the TRTA Hibiya Line.

Figure 15 Contact-Wire Cross Sections



Materials in Overhead Lines

The overhead line equipment consists of the contact wires, fixtures, and supports. The contact wire has a round cross section with grooves at the 2 and 10 o'clock positions, used for hanging the wire from a fixture. Conventionally, contact wires have been made of hard-drawn copper. Copper has very low electrical resistance and excellent corrosion resistance, making it an ideal material for contact wires. To provide higher mechanical strength, soft copper is hard drawn into contact wires.

In Japan, contact wires composed of copper with 0.3% tin are used widely to improve wear characteristics. Tunnel sections often use silver-copper alloy contact wires for extra heat resistance with the aim of preventing broken wires due to train fires. Recently, such copper-silver alloy contact wires are being replaced by copper-tin alloy contact wires.

A recent addition to the shinkansen are copper-clad steel contact wires designed to increase the wire tension for higher-speed operation. Figure 15 shows cross sections of the conventional type, and the two variations: copper-clad steel, and aluminium-clad steel.

The messenger wire is often made of galvanized stranded-steel wire for economy and high mechanical strength. Hard-drawn copper stranded wires are also used in many sections requiring larger current capacity.

Messenger wire fixtures require high-strength and corrosion-resistant materials, such as stainless steel and copper alloy. Aluminium alloy is preferred where weight reduction is critical.

Supports are often made of galvanized steel. High-quality, inexpensive porcelain insulators are common, but polymer insulators with excellent insulation characteristics have been introduced recently.

Maintenance of Overhead Lines

Overhead line inspection cars

The overhead line is a very long linear structure and, as such, is subject to sliding stress from the pantograph. It is also subject to a stress due to rain, wind, snow, ice, and other natural phenomena. Consequently, the overhead line is a potential source of accidents involving broken wires due to corrosion and wear. Such accidents require many hours for repair, so maintenance is essential.

Maintenance begins with accurate diagnosis of the present condition of the overhead line, often performed from a moving car. The shinkansen overhead lines are inspected every 10 days using 'Doctor Yellow', a seven-car electric facilities and track diagnostic system (*JRTR* 15, p. 43). Conventional lines use a two-car system. The measured items include the contact

External view of diagnostic car for electric facilities *(RTRI)* wire height above rail, deviation, wear, acceleration of pantograph head, and contact loss. For shinkansen, the measured data are processed by a central computer and the results are sent to the relevant maintenance crews.

Some items cannot be checked from a moving car. These include corrosion of the feeding wires and loose screws, which are inspected manually during normal maintenance work.

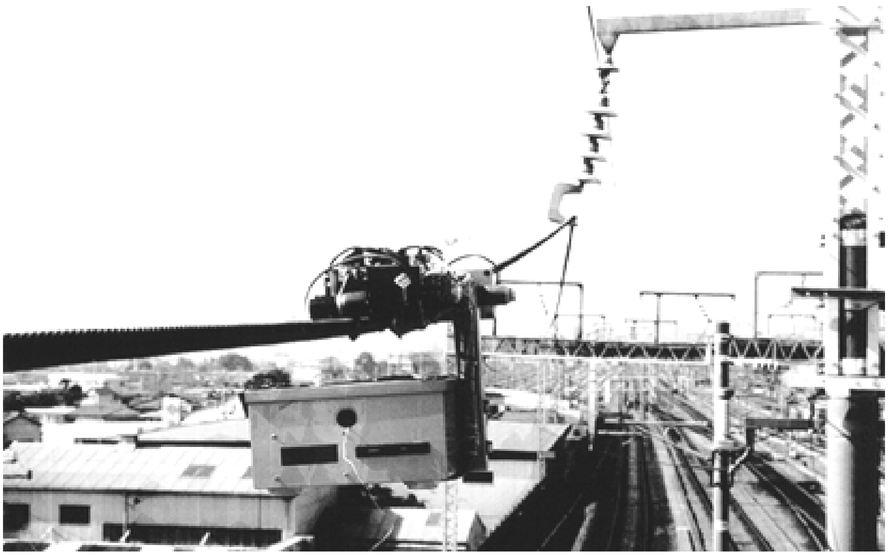
When lines need replacement, the work is performed using special cars. The above photograph shows a six-car system designed to replace shinkansen contact wires.

Automated diagnosis and repair is a recent topic for railway engineers and special efforts are being made to develop robots for this purpose.

Robotics

Overhead line systems require dangerous work at height. A self-powered feeding line robot with eddy current sensors has been developed and put into operation to locate cross-sectional area loss due to corrosion. ■

Contact wire replacement work car *(RTRI)*



Feeder line inspection robot *(RTRI)*

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