Rail Power Systems

METROS IN CHINA
DEVELOPMENT AND TECHNICAL FEATURES IN RAIL POWER SUPPLY

English

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Metros in China - Development and technical features in rail power supply

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The implementation of the economic reform program created the prerequisites for starting and consistently implementing a comprehensive expansion program for railways and local public transport. The metro systems in China have special technical and operational features that differ from systems in Europe, for example.

Metros in China - Entwicklung und Besonderheiten in der Bahnenergieversorgung

Durch die Umsetzung des wirtschaftlichen Reformprogramms wurden die Vorraussetzungen geschaffen, ein umfangreiches Ausbauprogramm der Eisenbahn und des öffentlichen Personennahverkehrs zu beginnen und konsequent abzuwickeln. Die Metrosysteme in China weisen technische und betriebliche Besonderheiten auf, die sich von Systemen beispielsweise in Europa unterscheiden.

Métros en Chine - Développement et particularités de l'alimentation ferroviaire en énergie

La mise en œuvre du programme de réforme économique a permis de créer les conditions nécessaires pour le démarrage et la réalisation d'un vaste programme d'expansion des chemins de fer et des transports publics locaux. Les systèmes de métro en Chine ont des caractéristiques techniques et opérationnelles particulières les distinguant, à titre d'exemple, des systèmes européens.

1 Introduction

In the early 1980s, the People's Republic of China began to implement its programme of economic reforms, which also included opening up to the outside world. As part of this programme, major efforts were made to expand local and long-distance transport networks in a short period of time and to upgrade them to the latest technology.

Figure 1:
Cities in China with metro systems (mainland, not including Hong Kong, Macau and Taiwan (figures and photos: RPS, authors)
red – as of late 2018, *blue* – start-up in 2019

For example, the first high-speed, long-distance railway line – the route between Beijing and Tianjin – was opened on 1 August 2008. The route covers a distance of over 100 km. By the end of 2018, i.e. just ten years later, the total length of the Chinese high-speed network was about 29 000 km. This accounts for around two thirds of the world's total high-speed rail network [1, 2].

The trend in local public transport is similar. Local rail transport systems in China are divided into:

1. Metro systems,
2. Light rail and tram systems and
3. Special railways.

The special railways include the *Translohr* system in Tianjin [3], various magnetic levitation systems (*Maglev*) and automatic transport systems, known as *Automated People Movers* (APM).

In addition to these, there are numerous trolleybus operations, wireless battery buses and, since late 2019, a system similar to a light rail in which vehicles travel without a contact line on asphalted roads and with normal rubber tyres [4].

Up until 1990, there were only three metro lines in the whole of mainland China – that is, not including Hong Kong, Macau and Taiwan. These were:

- Line 1 of Beijing Metro with a 10,7 km network length, opened in 1969

Table 1		
Cities in China with metro systems (end of 2018) [5]		
No.	City	Network length km
1	Beijing	617
2	Changsha	49
3	Changzhun	39
4	Chengdu	222
5	Chongqing	215
6	Dalian	54
7	Dongguan	38
8	Foshan	22
9	Fuzhou	25
10	Guiyang	34
11	Hangzhou	115
12	Harbin	22
13	Hefei	52
14	Canton (Guangzhou)	452
15	Kunming	89
16	Nanchang	49
17	Nanjing	177
18	Nanning	53
19	Ningbo	75
20	Qingdao	45
21	Shanghai	670
22	Shenjang	59
23	Shenzhen	286
24	Shijiazhuang	28
25	Suzhou	121
26	Tianjin	167
27	Urumqi	17
28	Wuhan	264
29	Wuxi	56
30	Xiamen	30
31	Xian	123
32	Zhengzhou	94

- Line 1 of Tianjin Metro with a 5,2 km network length, opened in 1980
- Line 2 of Beijing Metro with a 16,1 km network length, opened in 1984

These three lines have since been expanded to lengths of 31 km, 42 km and 23 km.

The next line was not opened until 1993, in Shanghai, with a length of 6,6 km.

Just 25 years later – that is, by the end of 2018 – the total length of all rail-bound local transport systems in mainland China added up to 5 761 km. Of these, 4 354 km are in metro systems, which have since been established in 32 cities [5]. This means that there are 1 407 km of light rail, trams and special railways. This does not take other electrical means of transport into account. Table 1 contains an overview of the metro networks in China, which is illustrated in Figure 1.

Figure 2:
Vehicles of the metro line to Capital Airport

The three largest metro networks in China are currently:

- Shanghai, with a network length of 670 km and 15 lines
- Beijing, with a network length of 617 km and 21 lines (Figure 2)
- Guangzhou/Canton, with a network length of 452 km and 12 lines.

The metro in Beijing is currently also one of the busiest local transport systems in the world: it handles 3,85 billion passenger journeys each year, amounting to around 10 million passengers a day. The current daily record was set on 12 July 2019, when 13,8 million passenger journeys were recorded. Overall, of the world's 15 most-used local transport systems, eight are in China.

To illustrate the figures involved, it is helpful to compare the networks sizes of the metro systems in London (*London Underground*), with a current network length of 402 km, and New York, with 380 km, which until relatively recently were the largest networks in the world. Passenger figures for London are 4,8 million journeys per day, or around 1,8 billion per year.

This means that, as with China's long-distance transport sector, the short-distance transport sector is the largest market for rail in the world, by a long way.

2 Basic principles of railway energy supply

The metro systems in China are generally operated on direct current, with the rated voltages
- DC 750 V and
- DC 1,5 kV.

New routes are constructed almost exclusively with DC 1,5 kV. Recently, there have been discussions about introducing routes with DC 3 kV, but so far without results.

One exception to this is the metro line to the new airport in Daxing in Beijing, which is operated with AC 25 kV 50 Hz [6].

The contact line for the DC metro lines is either a side conductor rail (so called *third rail*, generally at DC 750 V) or an overhead contact line, sometimes also designed as a rigid overhead conductor rail. In Guangzhou, two lines are operated with a DC 1,5 kV third rail system.

The contact line circuit essentially follows the principle of a two-sided supply, in which the tracks in opposite directions can be supplied separately.

Substations include solutions with the following components:
- Medium-voltage switchgear (ring or double feed)
- Rectifier transformer and rectifier
- DC switchgear with main busbar and with or without bypass busbar
- Contact line switchgear that enables shutdown of the substations by connecting adjacent feeding sections

Figure 3:
Brake resistor in a substation

The substations often contain either
- brake resistors (Figure 3),
- energy stores or
- inverters that are increasingly independent of the rectifier.

The aim of this is to generate as little heat in the tunnels as possible, including in braking resistances in the vehicles. The braking energy that is not used during travel is therefore either
- converted into heat at targeted locations
- retained for further use with the help of the energy stores, or
- fed back into the overlying three-phase current network.

Special solutions are presented in Section 3, taking two Metro Beijing lines as examples.

In China, metro lines are always constructed and operated line by line. This means that one city can have multiple operators and there can also be technical differences between the lines. The equipment on any one line is mostly uniform. When routes are extended, an effort is also made to ensure that new systems have the same layout as existing systems. It can therefore be assumed that the systems are highly standardised. Although planning services are provided by a total of eleven design institutes, the technical solutions are also comparable in the different cities. Equally, invitations to tender are mostly functional, which results in an overall standardisation of the systems.

When dimensioning the systems, the emphasis is on system availability and reliability. This is reflected in the layout of the substations, which can cope at least with a single component failure ($n-1$). In addition, total failure of a substation is also assumed in principle, so that the route can continue to operate uninterrupted with every second substation, as a last resort. Failure refers here in particular to the functional loss of the main busbar in a substation. As a rule, only a multiple failure would result in operational constraints.

Ultimately, this results in a relatively short distance between substations of 1,75 km, averaged across all contact line voltages, amounting to a total of 2 500 substations that have essentially all been built in China in the last 25 years.

A further peculiarity of the electric traction power supply for Chinese metro lines is that substations in important locations are staffed at all times. Sometimes, spare parts are also stored on site. This includes fully equipped switching trucks with DC fast breakers that can be replaced directly by local personnel when necessary. In some cities, routes with a side conductor rail are switched to a dead state outside operating hours to enable maintenance work.

3 Example: Beijing Metro

3.1 General information

The metro network in Beijing consists of 21 lines (not including Maglev and LRT) with a total length of around 620 km (as of late 2018, Table 2, Figure 4). The network is operated by three different companies, which are responsible for the infrastructure, vehicles and operation, respectively.

The 21 lines are operated at different rated voltages:

- DC 750 V 16 lines
- DC 1,5 kV 4 lines
- AC 25 kV 50 Hz 1 line

The lines also have different contact line designs. The lines with DC 750 V have a third rail, which is contacted either from above or from below. The lines for DC 1,5 kV have an overhead contact line system which, except in depots, is generally designed as a rigid overhead conductor rail.

Currently, additional lines with a total length of 333 km are under construction and a further 401 km

Table 2:
Overview of Beijing Metro lines, only metro/DC

No.	Designation	Length km	U_n V	Stations	v_{max} km/h	Contact line	Recovery system
1	Line 1	31	750	23	75	SCR	-
2	Line 2	23	750	18	80	SCR	-
3	Line 4	28	750	24	80	SCR	-
4	Line 5	28	750	23	80	SCR	Inv
5	Line 6	53	1 500	34	100	OCR	Inv, BR
6	Line 7	24	1 500	30	80	OCR	Inv
7	Line 8	46	750	35	80	SCR	Inv, BR, ES
8	Line 9	17	750	13	80	SCR	Inv, BR
9	Line 10	57	750	45	80	SCR	Inv
10	Line 13	41	750	16	80	SCR	-
11	Line 14	44	1 500	30	80	OCR	Inv
12	Line 15	41	750	20	100	SCR	Inv, BR
13	Line 16	20	1 500	10	80	OCR	Inv
14	Batong Line	19	750	13	80	SCR	-
15	Changping Line	32	750	12	100	SCR	Inv
16	Daxing Line	22	750	11	80	SCR	-
17	Fangshang Line	27	750	12	100	SCR	BR
18	Yanfang Line	21	750	9	80	SCR	-
19	Yizhuang Line	23	750	6	80	SCR	BR
20	Capital Airport Line	27	750	4	110	SCR	BR

OCR – overhead conductor rail, SCR – side conductor rail, Inv – inverter, BR – brake resistor, ES – energy store

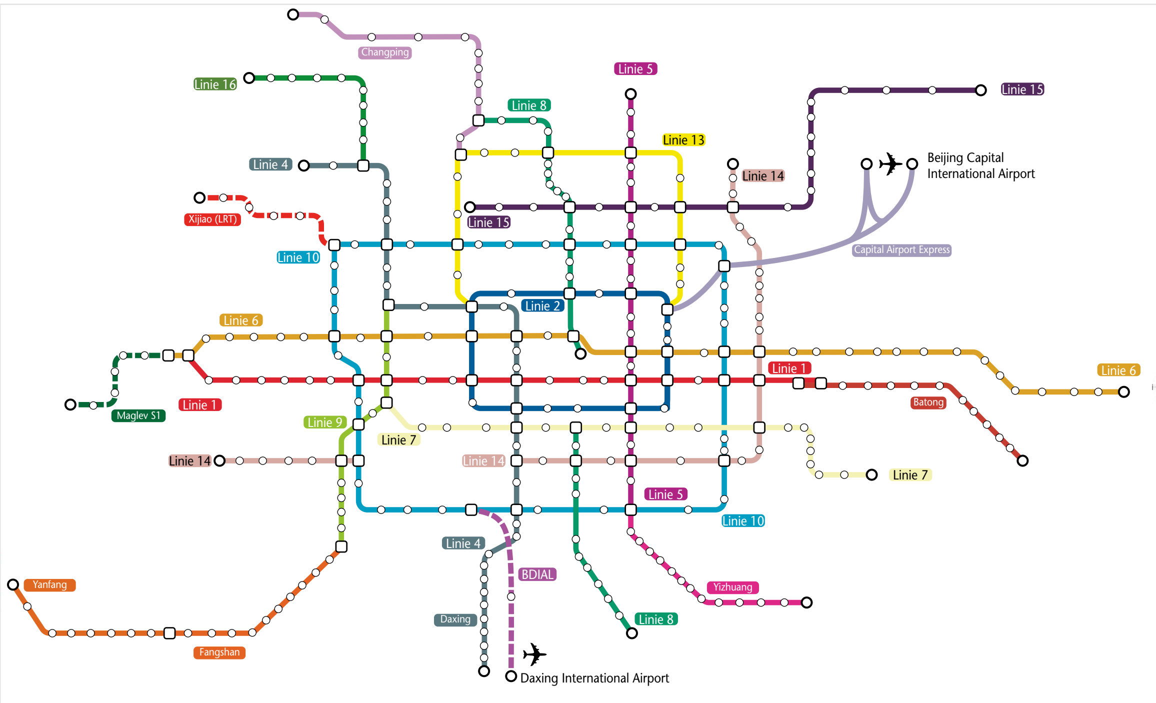


Figure 4:
Beijing Metro line network
dashed – not DC metro lines: BDIAL – AC 25 kV 50 Hz, magnetic levitation (Maglev S1) and LRT (Xijiao Line)

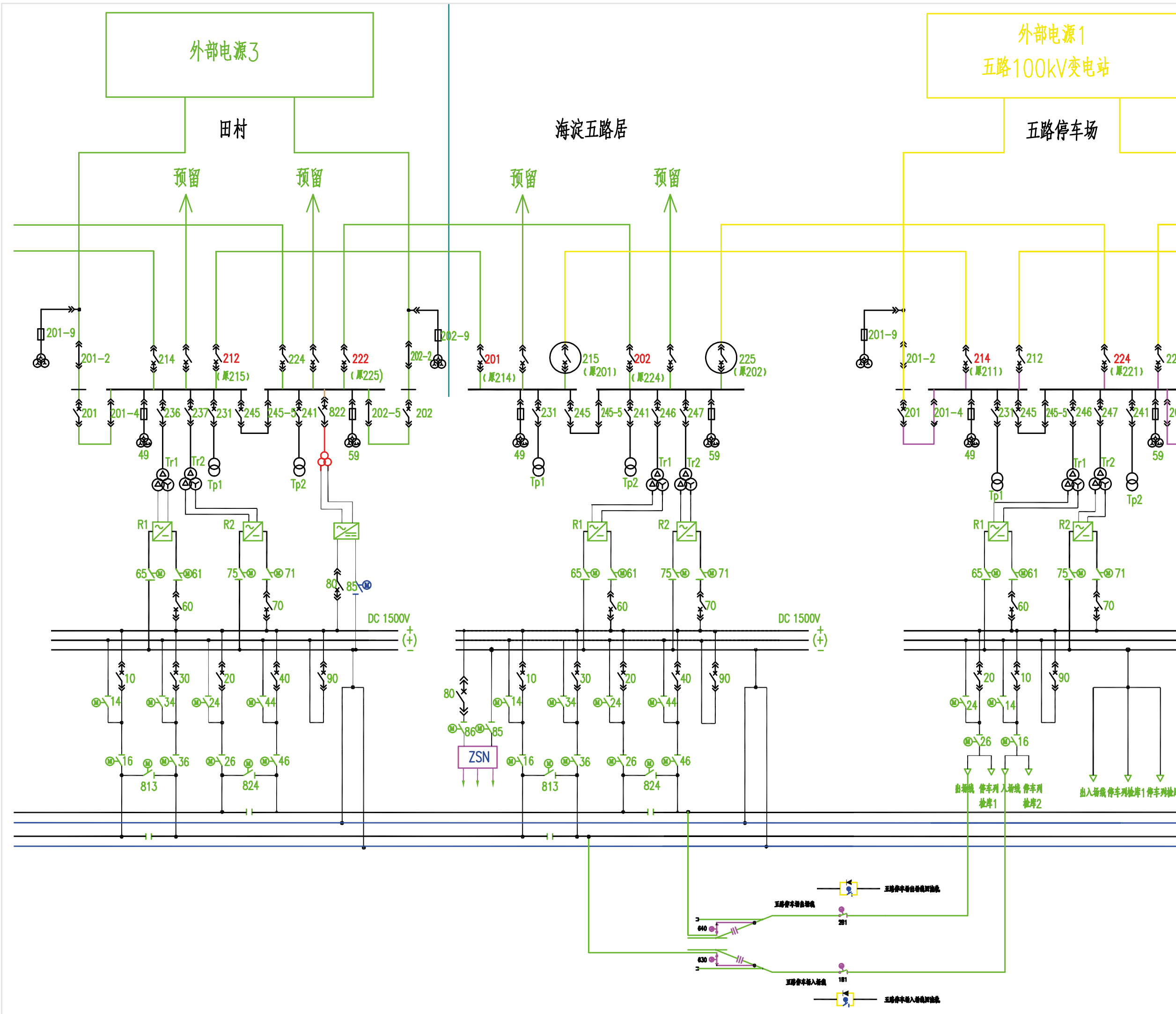


Figure 5:
Excerpt of the electric traction power supply diagram for Line 6 of the Beijing Metro

are in planning. By the end of 2021, the line network should therefore have a total length of 1 000 km. This means that around 100 km of new track is laid and put into operation each year.

The lines are mainly operated independently of each other. This is reflected in the fact that, for example, the lines have their own vehicles, with their own depots and their own control centres, although these are not ordinarily used. During normal operation, all the lines are controlled centrally from one control centre.

Different trains run on different lines, with those on Line 16 measuring 185 m in length, for example. The trains generally consist of eight vehicles with one driver's cab at each end. The interval between trains varies from 2,5 min to 8 min.

In total, Beijing has more than 350 substations, of which 100 substations are on lines for DC 1,5 kV.

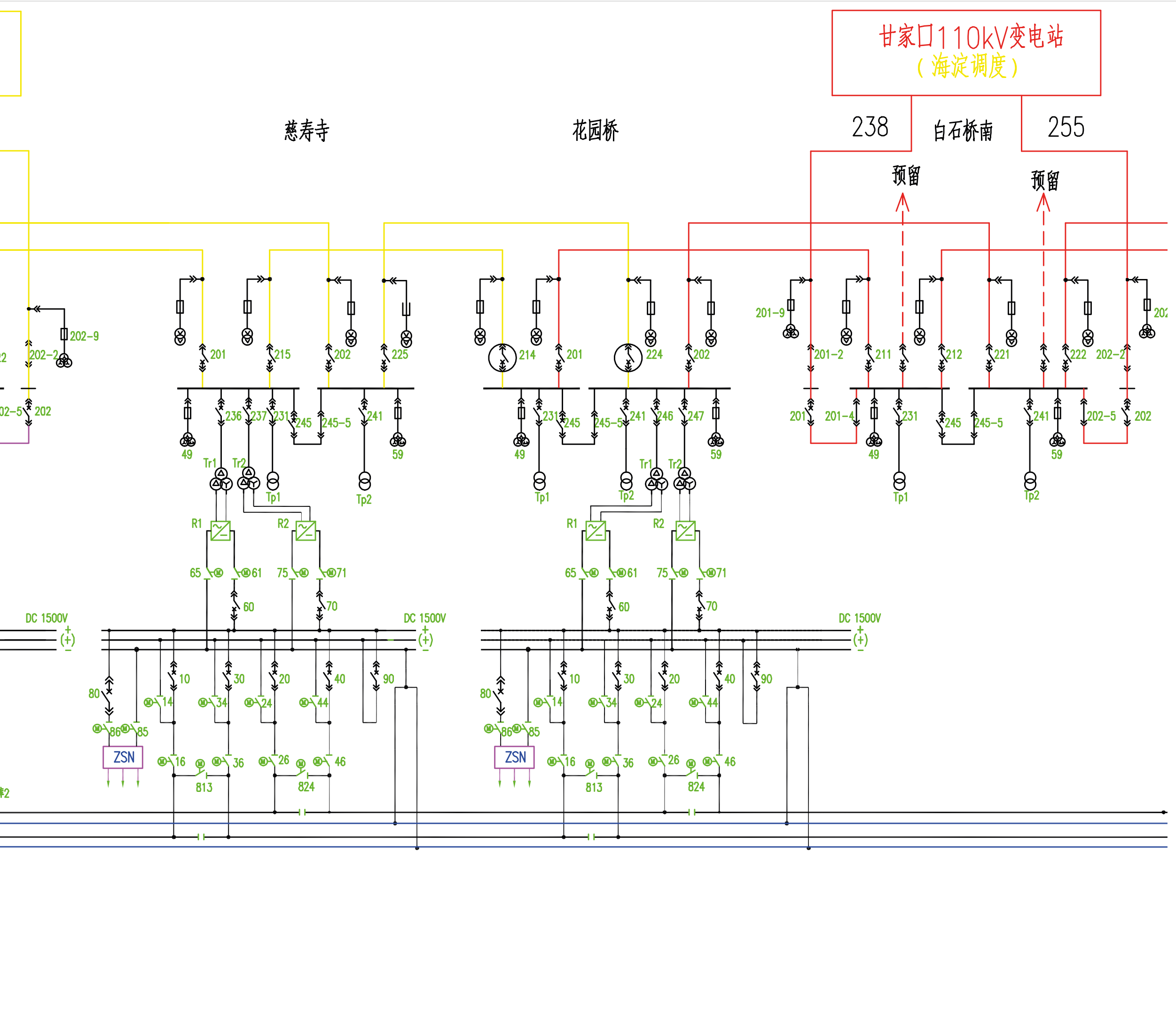
3.2 Railway energy supply for Line 6

3.2.1 Basic structure

The structure of the electric traction power supply is different from line to line, but it is basically standardised on each line.

Figure 5 shows an excerpt from the original overview circuit diagram for Line 6. This line is operated with DC 1,5 kV and has an overhead conductor rail. The diagram gives a comprehensive overview of the structure of the DC electric traction power supply. It contains all key characteristics, from the design of the medium-voltage supply through to the contact line feed. The excerpt of the diagram shows substations of different types:

- On the medium-voltage side
  - with supply from network nodes with a high-voltage connection and feed into the double



cable system (approximately every second substation)
  - only connected to the double cable system
- On the contact line side
  - as a substation along the line
  - as a substation for sidings and depots

The double cable system with 3AC 10 kV 50 Hz is routed parallel to the track and is operated by the local energy supplier.

The contact line sections are supplied from the substations, separately in each direction. This means that the two track directions are only laterally connected via the substation busbars.

There are 28 substations in total on the route. For a route length of 53 km, this results in an average distance between substations of 1,9 km. Given that there are 34 stations, there is therefore a substation at almost every station.

3.2.2 Medium-voltage switchgear

The medium-voltage switchgear 3AC 10 kV 50 Hz has a busbar that is divided lengthwise. One cable system is connected to each busbar section. In the substations, which are also connected by a 10 kV double cable to a 100 kV or 110 kV high-voltage substation, one cable is connected to each section of the busbar.

Two rectifier/transformer units are supplied from one of the two busbar sections via one circuit breaker. The power supplies for stations, tunnel systems and auxiliary systems were fed from the medium-voltage busbar also. The outgoing feeders of the rectifier transformers are connected in adjacent substations to different busbar sections in order to ensure an alternating feeding of the supply and a high availability.

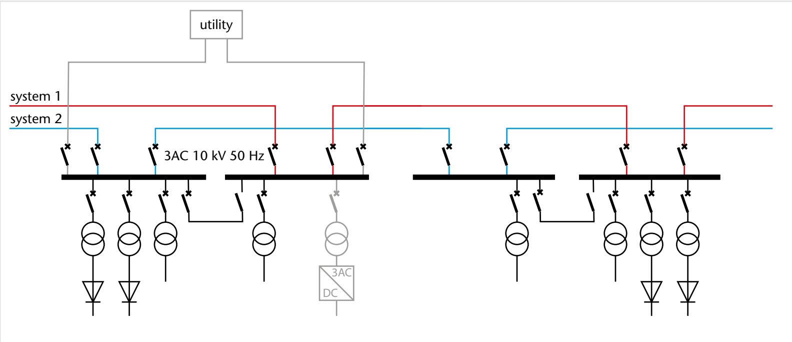


Figure 6:
Diagram of the medium-voltage supply

Figure 7:
Medium-voltage switchboard 3AC 10 kV 50 Hz in a substation

Figure 8:
DC switchgear *TracFeed® TDB* for DC 1,5 kV in a substation of Line 6 in Beijing

Figure 6 shows this medium-voltage system, including the structure of the busbars in the substations. Figure 7 contains a typical medium-voltage switchboard in a substation.

3.2.3 Transformer/rectifier unit

The rectifier transformers are triple-winding transformers with the vector group Ddy. There are 12 pulse bridges downstream of the transformers. Two transformer/rectifier units are operated in parallel. The plus pole of the rectifier output is connected by a DC circuit breaker to the main busbar of the DC switchboard; the minus pole is connected to the return line busbar.

The transformer/rectifier units have an output of 3 MW each, resulting in a substation output of 6 MW.

3.2.4 DC switchgear

In the example shown here – Line 6 – the DC switchgear (Figure 8) is designed with a bypass busbar system. Figure 9 shows a scheme of the DC switchgear layout.

In the substations along the line, there are four circuit breaker panels for supplying the contact line – two in each direction for two tracks. Added to these there is a bypass panel that can perform the function of a defective or shut-down circuit breaker during inspection work or in the event of a fault in one panel.

Another feeding line via a circuit breaker is used to supply the device marked as ZSN in Figure 5. In most cases, this is an energy storage device for storing unused braking energy. In older systems, a resistor is used instead of the storage device, generally a capacitor storage device.

As an alternative to this solution, and particularly with new systems, there are substations in which an inverter is installed between the DC busbar and the MV busbar in order to enable unused braking energy to be fed back into the MV network (Figure 10). This inverter has an output of 4 MW, which is less than the output of the supplying rectifiers.

The downstream DC switchgear is a contact line switchgear with disconnector switches that makes it possible to disconnect the branch from the line and to longitudinally couple the supply cables for one track. This makes it possible to completely separate out a substation from the line power supply in the event of a fault or maintenance work. The two-sided supply is then implemented between the adjacent substations; this switchgear contains no circuit breakers and therefore does not provide a protective function. These panels are integrated spatially into the substations (Figure 11).

3.3 Energy supply for Line 16

Figure 12 shows an excerpt of the energy supply diagram for Line 16. This line is 19,6 km long and has 26 substations. The route is also operated with DC 1,5 kV. As can be seen in the diagram, the substations do not have a bypass busbar system, unlike Line 6. However, the distance between substations is also less than 800 m here. The design of the electric traction power supply is essentially comparable to that of Line 6. One notable feature is that almost all the substations are supplied from an utility company network into the MV switchgears. Inverters are also installed in this line in order to recover braking energy and feed it back into the supplying medium-voltage network.

The different forms of notation in the diagrams indicate the different responsibilities and authors.

4 Outlook

As explained at the beginning, the total length of all metro systems in operation at the end of 2018 was 4 354 km in 32 cities. In 2019, a further 5 316 km were under construction, in part for nine additional cities. The number of cities with metro networks will

Figure 11:
Disconnector switch panel.

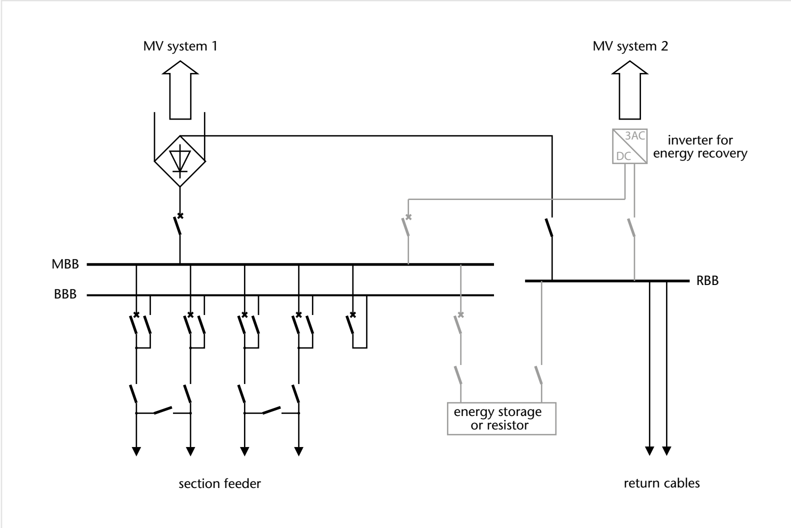


Figure 9:
Diagram of the DC switchgear with bypass busbar
MBB – main busbar, BBB – bypass busbar,
RBB – return conductor busbar

Figure 10:
Inverter for recovering braking energy and feeding it back into the medium-voltage system

grow to 41. In addition to this, a further 6 119 km of route are in the planning phase for a final total of 42 cities. This means that expansion of the metro systems in the People's Republic of China will continue at a very rapid pace in the coming years.

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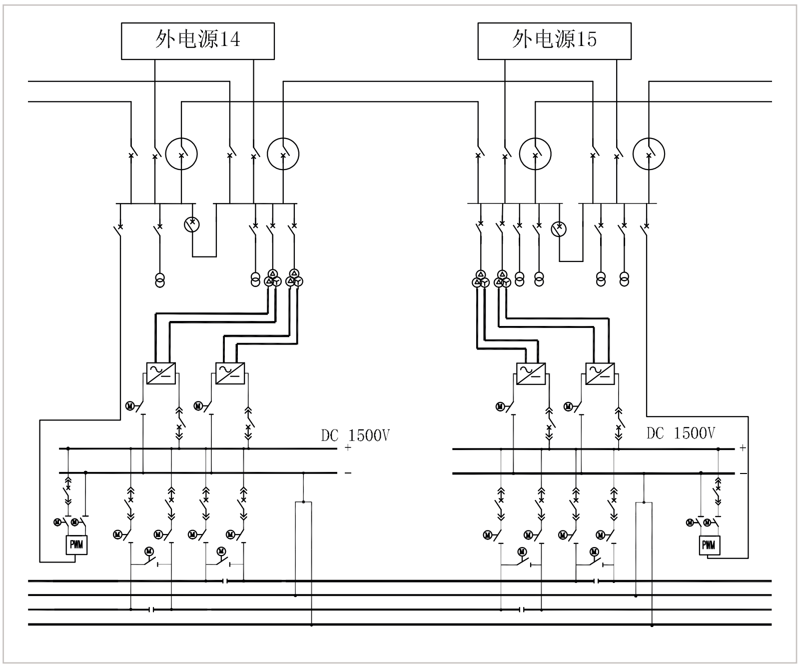

Figure 12:
Supply diagram for Line 16

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