Chapter 10

Converters, the mercury-arc rectifier and supply to electric railways

10.1 Introduction

Rectifiers were not needed when the light street railways of Europe and the USA were electrified in the 1880s using low-voltage DC supplied from batteries or dynamos in small lineside power houses. In the 1890s, the first heavy-duty rapid-transit railways were powered from DC generating stations which supplied power to conductor rails, or overhead contact wires. Rectifiers were not required for small projects such as the electrification of the Mersey Railway, Liverpool, in 1903. The need for rectifiers arose when small DC power houses were replaced by fewer large AC stations, which supplied AC transmission lines. The rectifier linked the AC supply with the low-voltage DC conductor rail. The development of the HVDC railway increased the demand for rectifiers which were generally rotary converters of the same design as those used on LVDC railways. The principle of the static rectifier was known by 1910, but the first experimental 'bulbs' were too expensive, too unreliable and too low in power capacity. The rotary converter was established, reliable, and long-lasting. Before 1930, it was able to convert powers far in excess of any practical battery of mercury-arc rectifiers. Rectifiers were also needed on many AC railways, to reduce the supply frequency to that of the AC motors.

10.2 Rectification of power supply

Rectifiers in railway service needed to be reliable, and capable of rectifying fairly large powers. This eliminated the purely mechanical rectifier, based on the synchronously vibrating polarised armature, and the various bridges, based on electric valves, in the form in which they appeared in the first ten years of the 20th century. These rectifying bridges, such as the Graetz Bridge, were developed for industrial purposes once high-powered 'valves' appeared, and the Graetz

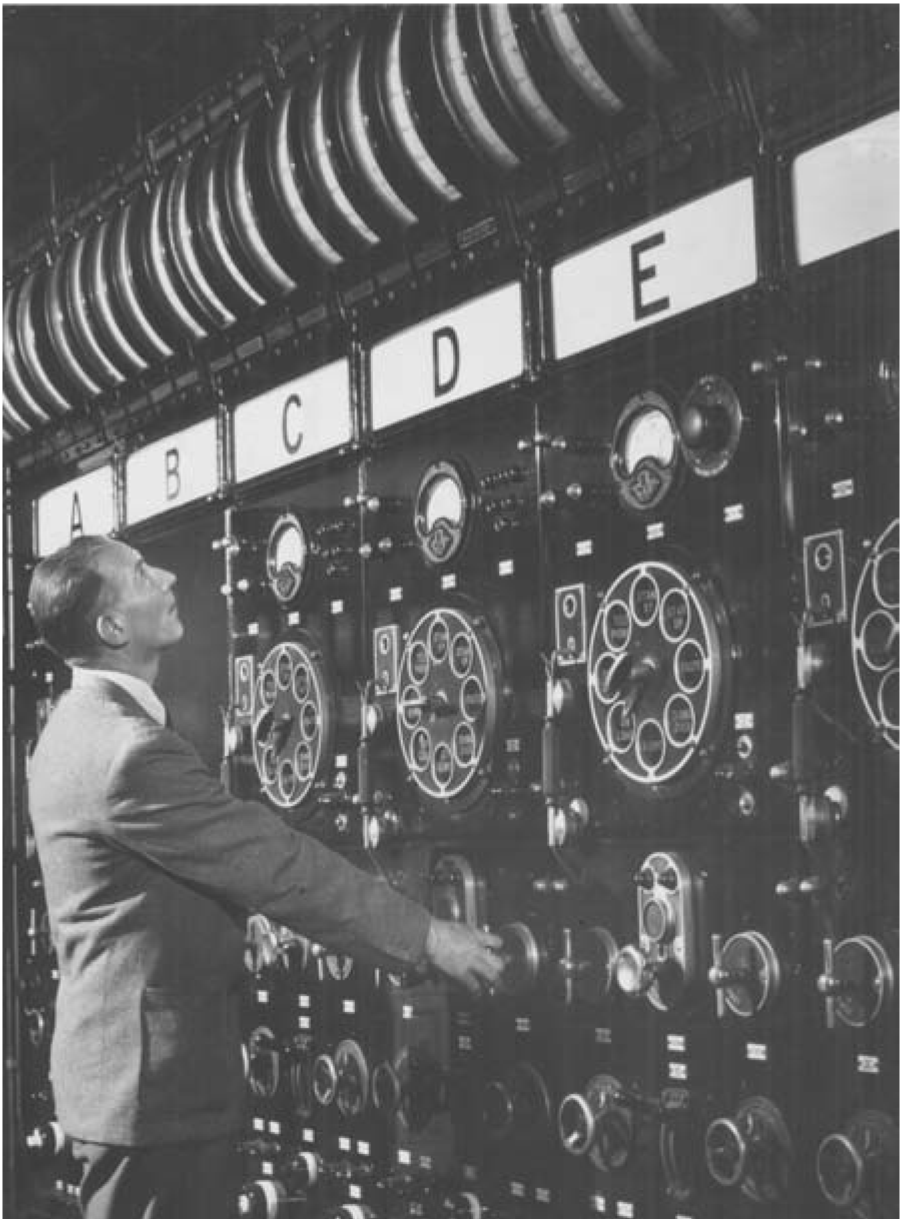

Figure 10.1 *Main control panel, Lots Road power station, Chelsea, London, in 1953. This governed the supply to the London Transport substations.*
Source: London Transport Museum.

arrangement was used with mercury-arc rectifiers in the post-Great War period. Though the potential of the mercury-arc rectifier was recognised in the period 1910–20, the general practice was to install rotary converters and motor generators in lineside substations. Though there were rare cases where converters were used in the inverted mode, to convert direct current to alternating current, the usual practice was to convert AC to DC, and it was traction requirements which focused attention on this particular electrical component. They were very reliable by 1910. There had been trouble with 'inverted rotaries' which could race or run away when excessive field weakening by lagging currents on the AC side caused dangerously high speeds of the converter armature, but speed controls using a separate exciter coupled to the converter shaft prevented this. Converters operating in the normal or AC to DC mode could race unless fitted with speed control. There was an instance where a synchronous converter was supplied from a 4000 kVA turbine-alternator, and fed a DC street railway, connected on the DC side in parallel with other substations and an older central 550 V station. When a steam valve failed and closed in the turbine-alternator, the converter became an inverted converter drawing power from the DC trolley system. The DC ammeter continued to read positively though the current had reversed direction, and the operator weakened the main field to reduce an apparent overload. The alternator and turbine raced and were wrecked. This accident led to the fitting of centrifugally operated circuit breakers, and reverse current relays on the DC side which broke the circuit if the converter operated in the inverted mode. These made the converter safe and suitable for traction purposes.

Both the LVDC and the HVDC railways required converter substations. One of the first DC railways to attract worldwide attention were the electric sections of the Chicago, Milwaukee and St Paul Railroad, which began working in 1915. These electrified sections made extensive use of substations. On the Missoula and Rocky Mountain Divisions there were 14 substations, each equipped with 100,000 V/2300 V transformers and two or three synchronous motor-generator sets feeding the overhead contact wire with 3000 V DC from two 1500 V DC generators connected in series. The distance between substations was 32 miles. The substations were of 4000 kW, 4500 kW and 6000 kW capacity, the total being 59,500 kW. Later, eight other substations were added with a total capacity of 28,000 kW and an ability for this to be increased to 40,000 kW. General Electric and Westinghouse supplied the equipment. The substations were manned, and photographs show substantial buildings with nearby operators' bungalows of a fair size. These CM & StP converters had a long life, and as late as the 1950s, the railway – facing a most uncertain future – installed second-hand electromechanical converters purchased from US electric railways dismantling their systems. General Electric rotary converters installed in Grand Central Terminal New York in 1916, to convert 11,000 V, 25 Hz AC to LVDC DC were still running in 1989 when the last four of the original ten were replaced by solid state rectifiers. This New York Central Railroad system LVDC electrification had pioneered automatic substations which needed no manning,

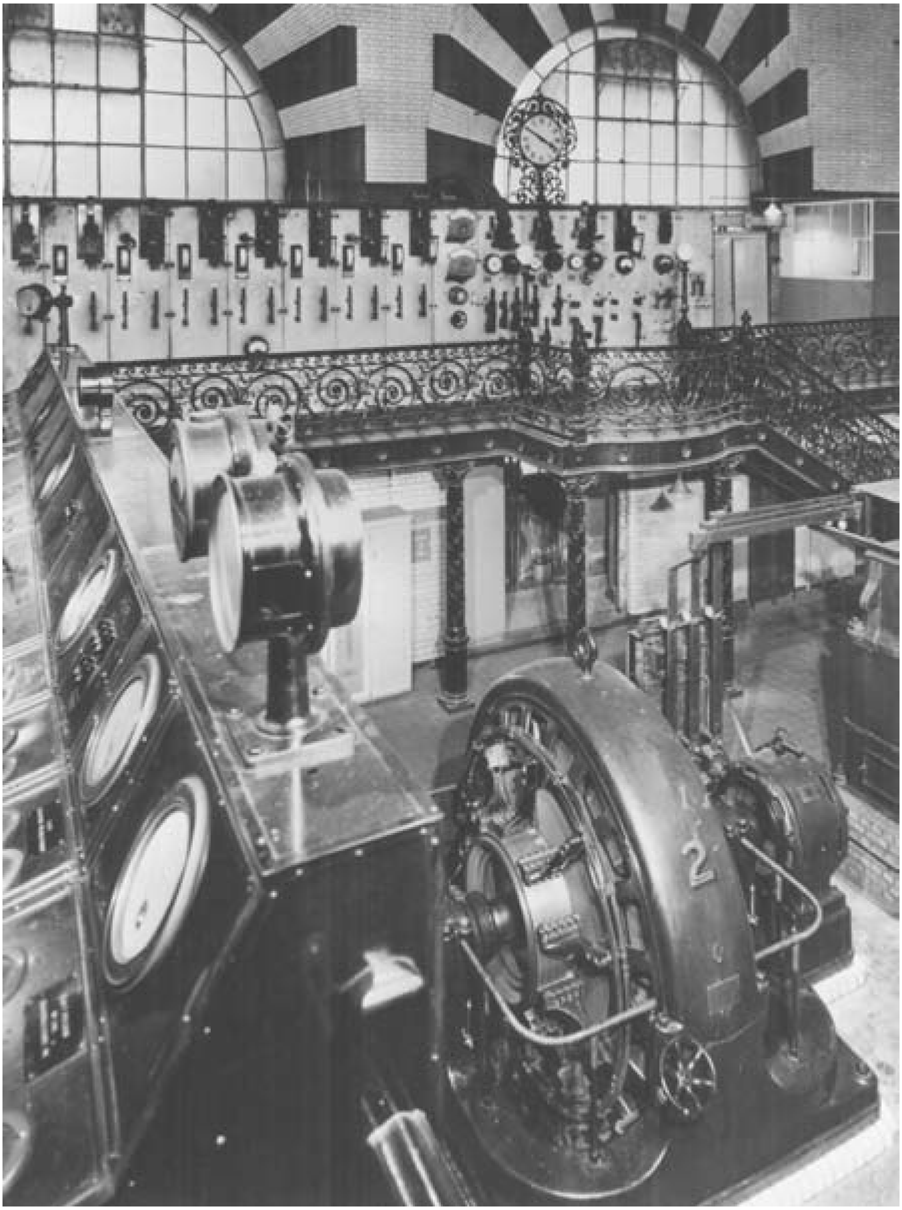

Figure 10.2 *Goldhawk Road substation London underground system showing electro-mechanical converter No. 2 with control and switch panels typical of the pre-1920 period.*

Source: London Transport Museum.

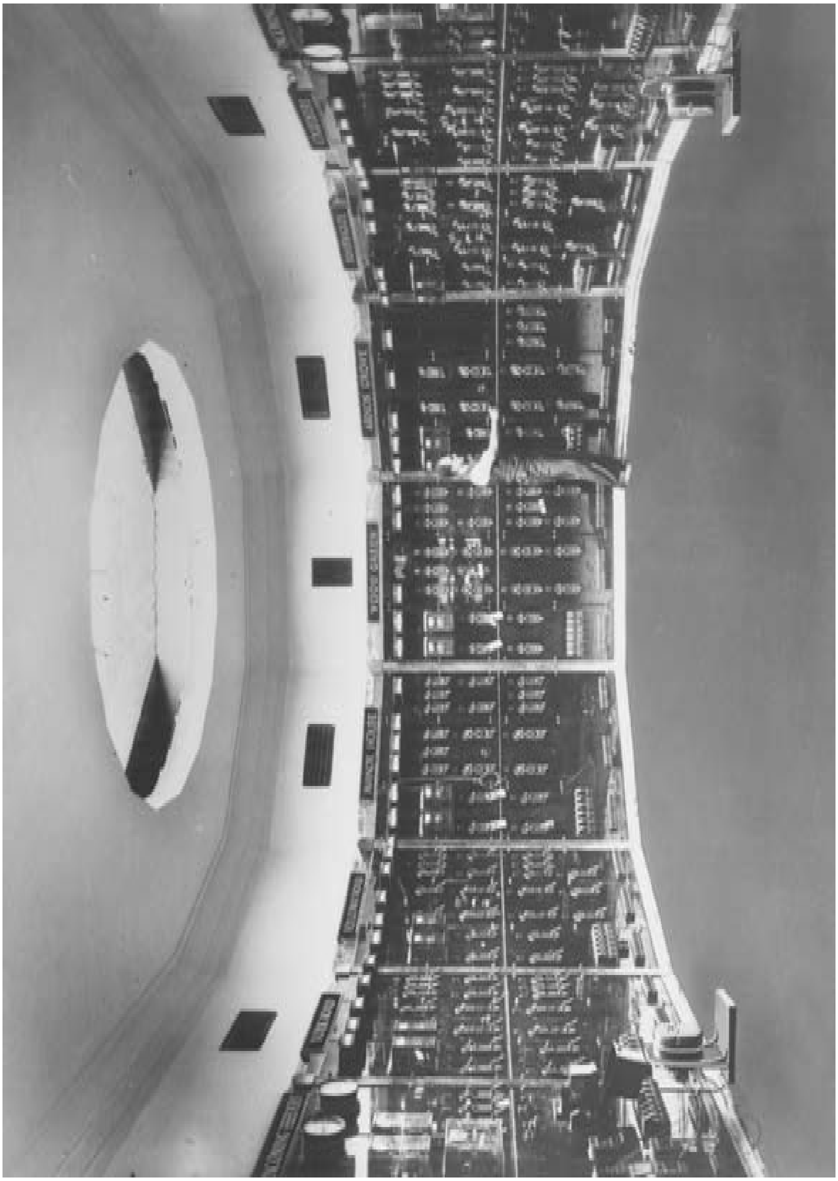

Figure 10.3 Power supply control room Wood Green substation, London, in July 1932.
Source: London Transport Museum.

and by the late 1920s, there were nine manned substations with a capacity of 66,500 kW and six automatic substations with a capacity of 18,500 kW. All used rotating electromechanical converters which proved eminently satisfactory as automatic control was extended from fewer centres and manning levels reduced. In Britain, the first unmanned rotary converter substation was installed by the Underground Company in 1924.

The mercury-arc rectifier was first used as a means of rectifying part of the power supplied, sharing substations with the older, larger rotating devices. The first extensive use of mercury-arc rectifiers was in the 1920s and 1930s, in the USA, when several of the interurban trolley systems were converted to HVDC, from LVDC or AC, and they were generally used to support rotary converters which dealt with the greater share of the power.

10.3 Development of the industrial mercury-arc rectifier

Twenty years of experimental work with electric arcs, mercury vapour, and evacuated vessels preceded the first attempts to make a rectifier based on the arc in mercury vapour. This type was called the static rectifier to distinguish it from the rotary or electromechanical type. Unidirectional current flow by means of an arc struck between a mercury pool and carbon electrodes was discovered by Jemin and others in 1882. In 1889, Fleming investigated unilateral conduction via an arc in air, and in 1892 Aron discovered that losses can be greatly reduced by causing the arc to be struck inside an evacuated vessel. Between 1894 and 1898, Sahulka studied the behaviour of atmospheric arcs between mercury and electrodes of iron or carbon. These were important experiments, but they were not carried out with rectification in mind.

Aron produced mercury vapour lamps between 1890 and 1892, but the successful commercial production of these devices is associated with Peter Cooper-Hewitt, who began commercial manufacture in 1900. To Cooper-Hewitt belongs the credit of making many of the fundamental innovations necessary for a successful commercial mercury-arc vessel, and for integrating them into a reliable, industrial device. His lamp of 1900 was based on the principle of using rectification via a mercury arc, and it formed the basis of the mercury-arc rectifier proper, which developed between 1905 and 1910 as the glass bulb rectifier. These rectifiers could handle only low powers, but were used to provide DC for the electrostatic precipitators employed to remove dirt from smokestack gas. By 1905, the principles of static rectification from a three-phase supply were well understood, and O J Lodge used four Cooper-Hewitt-type mercury 'lamps' or 'bulbs' arranged in bridge to supply the plates of his patent industrial smoke cleaner.

Cooper-Hewitt took out patents for the steel tank rectifier in 1908, and by 1910, General Electric and Westinghouse had constructed the first experimental types, though the glass bulb form remained the norm into the 1930s. Cooper-Hewitt also contributed greatly to the technique of using a controlled grid to regulate voltage in the rectifier, though glass-bulb grid-controlled rectifiers were not practical until developed by Langmuir and Prince and introduced in 1928, with grid-controlled steel tank rectifiers being introduced soon afterwards.

Glass bulb rectifiers were limited in capacity compared to steel-tank types, and it was limited capacity which determined the pace at which the static rectifier replaced the rotary type. Between 1912 and 1914, glass bulb rectifiers could carry more than 100 amperes, and by 1915 the first steel-tank rectifiers could rectify currents of circa 750A. Kraemer's type of steel tank rectifier, of 1919, first produced by General Electric in the USA, was the archetype for later development and led to large-scale commercial manufacture. By 1920, water cooled rectifiers were pioneered by Siemens-Schuckert, so that in the 1920s the reliable, high-capacity rectifier, with grid-control, water cooling, and steel-tank construction became available as a standard rectifier, which could convert industrial frequency AC to DC. It began to find use in railways for charging batteries to supply DC systems, but in the mid 1920s and after, it began to supplement rotary converters in the rectification of traction current, and by the 1930s was accepted as an alternative to the electromechanical converters which was much more compact and equally reliable. Its use was accelerated by the introduction of automatically regulated systems.

General Electric, Westinghouse, Brown-Boveri, Siemens-Schuckert, and AEG produced and developed steel-tank rectifiers, water cooling, and grid-control. There is evidence that the Americans generally led the way in arc-rectifer research, development and application though it can be claimed that they lost initiative to Europe between 1910 and 1920. Certainly the pioneer American work before the Great War was of immense significance. Early tests were made between 1908 and 1914 with glass 'Cooper-Hewitt valves' (Hewittic rectifiers), Westinghouse metal rectifiers, and General Electric metal rectifiers.

Cooper-Hewitt; Langmuir and von Issendorf solved the problem of backfiring. Bela Schaefer developed the metal-clad rectifier, a precursor of the metal-tank type. Kraemer, Toulon and Mittag perfected grid-control between 1924 and 1925. Prince and Langmuir introduced the first practical grid-controlled mercury-arc rectifier in 1928. General Electric, Westinghouse, Brown-Boveri, Siemens-Schuckert, and AEG, contributed to the development and production of rectifiers, including the steel-tank, water-cooled type with grid control. Brown-Boveri pioneered the European multiple-anode steel-case rectifier in 1913, which became a widely used form. By 1925, the industrial mercury-arc rectifier was established. In the development phase, backfire was a serious problem, arising from short circuit of the supply transformer, between anodes, caused by two arcs merging. Backfire damaged seals, and could shatter a glass bulb vessel, and precautionary shielding of anodes was required, but Langmuir and von Issendorf were able to prevent it by the mid-1920s. Capacity per unit was raised and groups of arc-rectifiers could handle a significant percentage of substation power flow, and from 1925 they supplemented the rotary converters.

The multi-anode, steel-tank rectifiers of the 1920s had capacities per unit much higher than those of the glass bulb type, though they required vacuum tight seals and automatic auxiliary pumps to keep the tank free of gas. Reliability was improved by water cooling the arc, and by using heating coils to keep anode temperature above the condensation temperature of the mercury vapour at low load. Arc length had to be increased in the multi-anode rectifier to reduce the chance of backfire, and this lowered efficiency by increasing the drop in arc voltage.

In Europe, metal-tank, mercury-arc rectifier substations were used in Switzerland as early as 1915, but they were only of 240 kW capacity. By 1920, glass-bulb rectifiers were used in Britain to charge low-capacity arrays of batteries from AC supply, and after 1923, they found similar use in France. By 1930 the static rectifier converted AC supply to DC, to feed the conductor rail of the LVDC railway, and the overhead contact wire of the HVDC system. In the 1930s it began to supplant rotary sets for frequency changing on AC lines. However, rotary sets worked well and had long working lives, so that many were left in place long after the mercury-arc rectifier became standard.

At this time, larger capacity Brown-Boveri gridless mercury-arc rectifiers were used in France to supply 1500 V DC. These were expensive, but were lighter and smaller than rotary converters. Britain was slow to develop and use the mercury-vapour rectifier, despite the early use of Cooper-Hewitt valves by Lodge for smoke-cleaning before the Great War. The first ‘all British’ steel tank rectifier was not installed until 1930, when the British Thomson-Houston Company supplied a 1500 kW, 615 V unit to London Underground railways. Bruce Peebles & Co. started the regular production of steel-tank rectifiers in Britain, and English Electric followed in 1932. Glass bulb rectifiers were used in Britain before the steel-tank form, and both kinds were widely employed after 1930. By 1935, the capacity of the glass-bulb type was about 500 A DC, 600 V. British industry was slow to enter mercury-arc rectifier research, design and manufacture, but rapid progress was made during the 1930s, and by 1939 models were on the market equal to any produced in the USA or Continental Europe. However, the Americans and Germans led in research.

By 1930, the mercury-arc rectifier was the best method for rectifying and inverting current passing to and from transmission lines and industrial circuits. It was superior to the rotary converter, and to alternatives which were sometimes suggested. These included the air-blast rectifier of Erwin Marx, which used an ultra rapid series of compressed air jets to blow out the arc of an AC supply when it passed in one direction, but permitted it to flow in the other direction. Several very large examples were built, and found a limited – but unsuccessful – use in Germany in the period 1930–45. The advent of mercury-vapour systems for rectification, inversion, and frequency changing facilitated the construction of power networks, and it was normative in stationary service by 1930.

Attempts to use static rectifiers in locomotives service were less successful and the reliable locomotive-mounted rectifier required the solid-state industrial devices of the 1960s. Until then, the rotary converter was used in various forms of converter locomotives. Locomotive-mounted static rectifiers were tried as early as 1908 in the USA when Westinghouse used two glass bulb mercury vapour valves to rectify 3.3 kV, 25 Hz AC to 600 V DC. In 1913, General Electric mounted rectifiers on a wagon to supply a 600 V DC motor car, but the rectifiers proved too fragile for locomotive use. Success was achieved however with stationary rectifiers in substations, though low capacity limited application. Between 1913 and 1914, Westinghouse rectified 11 kV, 25 Hz AC to 750 V DC on the Pennsylvania Railroad, and at Grass Lake, between 1912 and 1915, experiments showed that a 5000 V DC trolley wire could be supplied through static rectifiers, though this line reverted to moderate tension DC after the trials. Tassin, Nouvion and Woimant refer to a test, on the Kalamazoo-Grand Rapids line in Michigan in which the voltage in an isolated third rail was raised to 5000 V DC. The Europeans were quick to take up research in this field, and for a while led in research and development until American companies regained the initiative in the 1930s and 1940s.

Between 1930 and 1960, many improvements were made to the mercury-arc rectifier, and the market was dominated by a limited number of types associated with the leading electrical manufacturers, made under licence in different countries. The best known was the ‘ignitron’, called after the trade name of a patented device for striking the arc, which was developed both by Westinghouse Electric and General Electric. It originated in a discovery of 1933 that the passage of a current from a high-resistivity rod to the mercury in which the rod was partially immersed, would create an arc within a few microseconds at the junction of rod and mercury surface. Another well-known type was the ‘excitron’ associated with the Allis-Chalmers Manufacturing Company. This was a single-anode rectifier, in which the ignition coil was energised, so that the cathode was ready to conduct current when the anode fired. There were many variants, often devised to get round patents.

10.4 The mercury-arc rectifier in railway traction

An early electrification scheme to use mercury-arc rectifiers was on the Midi railway in France, which used 1500 V DC as standard, influenced by studies of American HVDC installations and by a belief that rectifying higher voltages using rotary sets in series, or using mercury-arc rectifiers, would not be successful at that date. In the event, five mercury-arc rectifiers were tried, alongside rotary converters, and they worked well. They did much to encourage wider employment of static rectifiers in Europe and the USA.

Writing in 1922, Carter provides a useful summary of attitudes to the several systems associated with rectification in railway service at that date. He is rather conservative in his attitude to the mercury vapour rectifier:

(The mercury vapour rectifier) has now been developed in form and capacity suitable for the requirements of railway supply, and although it has hardly yet attained the condition of reliability needed in such work, its development has disclosed no insuperable defect. It should therefore be watched, as a development which may prove to have considerable influence on the future of railway electrification.

Carter is apparently referring to the glass-bulb type. He was certainly aware of the great potential of the mercury-arc rectifier, though he remarks that complete substations would be less efficient than those equipped with rotary units because of less efficient transformers, and increased losses in auxiliaries. Overload capacity was less than with a rotary set, and installed capacity needed to be greater on this account. Cost (in 1922) for a complete installation was higher than for an equivalent plant using rotary units. However,

The mercury vapour rectifier does not impose a limit on the frequency of supply, nor on the voltage of the output. It accordingly appears a fitting development to meet the needs of high voltage continuous current railways taking power from industrial supply. Although the single-phase AC commutator motor was established in Europe and the USA by 1910, and the universal series motor, able to run on AC and DC, found some use on railways including the New York, New Haven and Hartford RR, which had DC and AC sections, the favoured motor was the DC type, usually of the Sprague nose-suspended type, ... although further experience is necessary before it (the rectifier) could be recommended without reserve for such work.

Carter looked forward to the time when mercury-arc rectifier substations would be unmanned, but he did not think this was then in sight,

... for the (mercury) rectifier requires more skilled attention than the rotary. A result to be expected from the sudden changes in line voltage, produced when the arc shifts from anode to anode, is that this form of converting plant will cause much greater interference with neighbouring communications circuits than the usual forms with rotating machinery.

However, this automatic regulation of arc-rectifier substations was to be achieved by 1927 as described below. Carter also referred to the increased use, particularly in the USA, of unattended or unmanned substations, using rotary sets, such as became common in the 1920s. He also makes the very important point that the use of regenerative braking, with the return of energy to the contact wire, and through the substation, demanded reversible converters or rectifiers, which ruled out the mercury vapour type at that time and encouraged the retention of already installed (reversible) rotary converters and motor generators on mountain railways like the Chicago, Milwaukee & St Paul Railroad. Carter makes passing reference to the rectifier locomotive, taking single-phase supply from the contact wire, to be rectified for use in DC motors, but he indicates that trials so far carried out with such machines were not successful.

By 1926 and 1927, mercury-arc rectifiers were being installed in the lineside substations of heavy-duty electric railways to supplement the rotary converters, or to rectify current to charge storage batteries which improved load factor or supplied emergency power. One early example is the electrification of the Illinois Central Railroad, reported in the *General Electric Review* of April 1927. One interesting feature was that the power companies owned the substations, and operated them, selling the rectified power to the railway's 1500 V DC contact wire. The Illinois Central ran ten-car multiple-unit trains needing 5250 kW during acceleration, and 1140 kW for average running. The substations used 3000 kW synchronous converters and mercury-arc rectifiers to convert 60 Hz AC supply into 1500 V DC. Provision was made for 'remote supervisory control for indication to, and control by, the railroad's power supervisor of all d-c feeder circuit breakers in substations and at sectionalization points.'

The substations were six miles apart. There were seven in all, with a total installed capacity of 42,000 kW, of which 9000 kW was rectified by four mercury-arc rectifier sets, two of 3000 kW capacity, and two of 1500 kW capacity. The rest of the power was converted by 3000 kW synchronous converter sets. The *General Electric* report of 1927 stated that:

> The rectifier sets consist of two 750 kW or two 1500 kW, 1500-volt bowls operating in parallel; and, in all cases but one, are installed in substations with synchronous converters and operate in parallel with the converters in the same substation. The rectifier overload ratings are 150 per cent rated load for 20 minutes, 300 per cent for one minute.

The voltage-regulation requirements of the railroad were that the voltage at the substation bus should not fall below 1400 V during normal load conditions, and both converters and rectifiers worked well. A major step forward in substation design was the use of the first automatically controlled arc rectifiers to supply traction current to a HVDC rapid-transit railway. This was reported in the *General Electric Review* for July 1927, and the editor introduced the paper with the words:

> So far as we know, this is the first description of the automatic control of a mercury arc power rectifier. The instructive information given possesses more than the interest of novelty because the control functions strictly in accordance with the high standard previously set by the automatic control of rotary conversion apparatus.

This claim for priority may be for America only, as later the paper remarks that 'this represents the first application of 1500 volt rectifiers and of 1500 volt automatic rectifier control in this country.' The rectifiers, of the steel tank type, were installed with new rotary converters during the reconstruction of the Chicago, South Shore & South Bend Railroad which started in 1925 and which converted the 6600 single-phase AC system to 1500 V DC. Power supply was from a 33,000 V line which fed eight substations, where conversion and rectification to 1500 V DC took place. The arc rectifiers did not share substation space with rotary converters, but were in substations of their own. One substation contained a 1500 kW arc rectifier, and three contained one 750 kW arc rectifier each. The other four substations contained two 750 kW rotary converters each. Two substations with rotary converters were partially automatic, and two were automatic. All the arc rectifier substations were automatic. Out of a total substation capacity of 9750 kW, 3750 kW was rectified using automatically controlled mercury-arc rectifiers. Arc-back or backfire was still considered to be a potential hazard, and a high-speed circuit breaker, connected in the positive lead, was arranged to trip on reverse current flow. This opened the DC side, and via an interlock on the high-speed breaker, simultaneously tripped the oil circuit breaker, energising the reclosing relay, which reclosed the breaker after a delay. Normal operation should follow, but if a second arc-back occurred the process was repeated. If a third backfire took place within a set time period, the station was automatically shut down for inspection. The 1927 article claimed that automatically controlled mercury-arc rectifiers were no more complicated than rotary converters, and were equally reliable. With the introduction of these automatic stations, use of the static rectifier spread rapidly, and in the 1930s it became the favoured method for rectifying from AC to DC; for frequency changing; and for inversion in connection with HVDC transmission lines.

10.5 British railway rectifiers

Britain lagged in the development and use of the mercury-vapour rectifier, and the first 'all British' steel tank rectifier was not installed until 1930, on the London Underground system, and English Electric did not begin regular production of the steel tank rectifier until 1932. Both steel tank and glass bulb forms were widely used, and by 1935 the maximum capacity of a glass-bulb type was about 500 A DC with a voltage of about 600 V. British main line railway companies, and London Transport, began to make extensive use of static rectifiers from 1930 onwards, often installing the multiple anode, steel-tank type with automatic control. They were used alongside older, as well as newly installed, rotary converters. The London Midland & Scottish Railway first used one in June 1931, and they were installed in new substations serving the LVDC conductor rail network in the London area, on Tyneside, and on the HVDC lines in the Manchester district. In the latter area, the electrification of the Manchester, South Junction & Altrincham Railway in 1931 used both new rotary sets and mercury-vapour rectifiers. AC supply was at 11 kV, and was converted to 1500 V DC for the overhead contact wire. BTH supplied ten 750 kW, 1500 V DC rotary sets in 1929, plus a steel tank rectifier of 1500 kW capacity in 1930. The Timperley substation contained the BTH 12-anode, steel-tank mercury-arc rectifier, the first time this type was used on a British railway. It was widely installed in the 1930s throughout London Transport. An early British substation, with automatic static rectifiers, was Balham on the London Transport system. Eventually the mercury arc rectifier was used on such historical systems as the Isle of Man electric railways, and Volk's electric railway in Brighton.

In 1932, two BTH rectifiers, of 1200 kW, 630 V, were installed in the Hornchurch substation on the LMS Barking-Upminster line. In Britain, the

Figure 10.4 *Arnos Grove substation on the Piccadilly line (London) in 1933 showing new 12-anode mercury-arc rectifier.*
Source: London Transport Museum.

advertisements in the *Railway Gazette* trace the progressive installation of this form of rectifier. The issue for 19 October 1934 announced that BTH rectifiers with a total output of 37,000 kW were working on the London Passenger Transport Board, quoting as example three 1500 kW, 630 V, rectifiers installed in Barons Court substation. The issue for 11 January 1935 announced the installation in 1932 of two 1200 kW, 630 V BTH rectifiers in the Hornchurch substation on the LMS Barking-Upminster line, and claimed that BTH rectifiers with a total output of 42,900 kW had been installed on British railways. *Railway Gazette* for 27 July 1934 carried a notice announcing the anticipated use of the mercury arc rectifier in railway service as a frequency converter for AC railways.

In the case under notice, a converter of 3,600 kVA capacity will change three-phase 45 KV. 50 cycle supply into single-phase 15 kV. 16.66 cycle current for use in the overhead contact lines of the Basle-Schopfheim-Zell-Sackingen division of the German State Railway, and will replace rotary machines and batteries which have been in service since the inception of the electric service in 1913,

It was claimed that large scale tests of the equipment at the Berlin works of AEG showed an efficiency 'a good deal higher' than that of rotary frequency converters, and substantial reductions in working costs. It was concluded that:

. . . it may be anticipated that mercury vapour frequency converters will have just as wide a field of application in single-phase systems as the mercury rectifier now enjoys in d.c. traction.

A series of articles on mercury-arc rectifiers, published in *Railway Gazette* in 1934, compares the physical construction, and relative merits of both the glass bulb type, and the steel tank type, at a time when both were finding increased use in traction. The increased capacity was the chief feature of the steel tank form:

The greater mechanical strength of steel compared with glass enables direct current outputs up to 5000 kW or even 8000 kW if required to be obtained from a single steel-tank unit, compared with about 250 kW maximum output from a glass bulb unit, at 500 volts in each case.

However, granted that many substations had a capacity of about 2500 kW, this could be provided by two banks of glass-bulb rectifiers, with each bank having six or eight banks in parallel, or by two steel-tank rectifiers, or even by one. The report stated that both solutions were found in practice, each with advantages of its own. By 1934, the steel-tank rectifier was of proven reliability ('risk of breakdown is almost negligible') and efficiency was 95–96 per cent or better at loads from 0.25 to 1.25 rated output. A review of constructional details is given in the *Railway Gazette* paper of July 1927. The article reports on the 23 Bruce Peebles steel tank rectifiers, rated at 2500 kW being built for the Southern Railway electrification extensions between Eastbourne, Lewes and Hastings, and around Sevenoaks. Also shown is one of three 1500 kW GEC steel tank rectifiers installed at Chiswick Park substation on the London Passenger Transport Board railways. The Hammersmith to Hounslow and South Harrow extension of the LPTB Piccadilly line required 13 1500 kW, 630 V rectifiers in five substations. These five substations were normally unmanned, and four were remotely controlled from a room in the Alperton distribution station. By the early 1930s, the outstanding problems of the automatic, mercury-arc rectifier substation were solved, and the arc rectifier station became the type for future development.

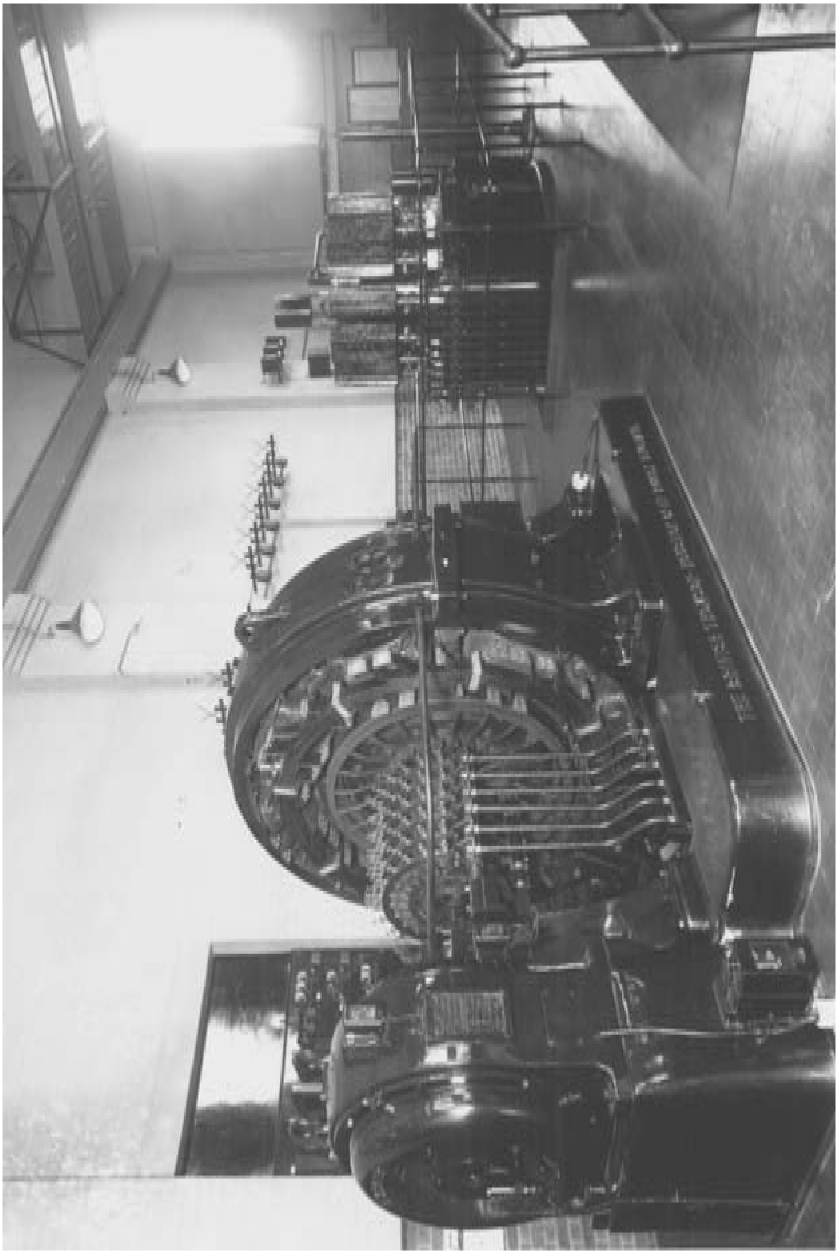

Figure 10.5 *Hendon substation, London, in 1931 showing British Thomson-Houston rotary converter and 1500 kW mercury-rectifier.*
Source: London Transport Museum.

The engineers of London Transport have always enjoyed a reputation for leading innovation, and were responsible for the first large-scale use of water-cooled, continuously evacuating, mercury-arc rectifiers in Britain's railways. The multi-anode, cylindrical tank, automatically controlled static rectifier became practically standard throughout London Transport after 1930 though they continued to work alongside rotary sets dating from an earlier era. Hendon substation was one of the first to be equipped with multi-anode steel tank rectifiers as well as rotary sets, and this type was installed at Arnos Grove, 1933, Wood Green, 1935, and Leicester Square, 1935. By 1935, BTH claimed that their rectifiers provided a total output of 42,900 kW for British railways, mostly for London Transport . British manufacturers were energetic in exporting their rectifiers. In 1936, English Electric and Metropolitan Vickers supplied steel-tank rectifiers (2000 kW and 2500 kW) for Polish railways' 3000 V DC electrification programme, and after the war British firms took part in reconstruction work in Poland.

A great improvement was the introduction of polarised grids, which enabled the current from regenerative braking to be returned to the supply, thus removing a major disadvantage of mercury-arc rectifiers. Railway substations with polarised grids were working successfully in South Africa by 1938. Both the glass bulb type and the steel tank type of rectifier were widely used. In fact, the Hewittic glass-bulb type replaced surviving rotary converters on London Transport in the period of refurbishment in the 1950s and early 1960s, when Russell Square, Bond Street, Charing Cross, Baker Street, and other substations were modernised.