철도 전기 시스템
Rail Road Electric Traction System

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ABSTRACT

In this paper, the details of electric traction voltages which are widely used for metro and mainline trains are presented. The problems encountered in catenaries, pressure of the pantograph pan, catenary contact cross sectional area, materials etc are well covered. Catenary height from the rail for main line, bridges, sheds etc is discussed. The catenary running details and switching of one catenary to another are explained. The dead zones in 3 phase grid as well as in DC are presented here. The pantograph structure, blades, shoes etc. for AC/DC EMUs are dealt. The schematic diagram for electrification systems used for railways are given and explained with typical electrical parameters of Indian Railways.

1. **Introduction:**

There is a wide variety of electric traction systems around the world, which have been built according to the type of railway, its location and the technology available at the time of the installation. Many installations seen today were first built up to 100 years ago, some when electric traction was barely out its diapers, so to speak, and this has had a great influence on what is seen today.

In the last 20 years there has been a gigantic acceleration in railway traction development. This has run in parallel with the development of power electronics and microprocessors. What have been the accepted norms for the industry for, sometimes, 80 years, have suddenly been thrown out and replaced by fundamental changes in design, manufacture and operation. Many of these developments are highly technical and complex, the details of which are therefore beyond the scope of this paper. Because these changes have been so rapid, and there are still plenty of examples of the original technology around and in regular use. Here most of the discussions are based on Indian Railways.

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2. History of electrification

The first electric train was introduced in central part of India, Bombay (Mumbai) Metro on February 3, 1925. Later in 1930, the metro electric train service was extended to Poona. India was one among the first few countries in Asia to receive electric suburban train service. The other two countries are Japan and Indonesia. In 1905, Japan was running electric railcar services in small scale and in 1911 German-built electric locomotives were introduced in Japan as a major transport system. In 1919 the first,the first entirely Japanese electric locomotive was built (a class ED-40). In Indonesia, the first electrified section (1500V DC) of the State Railways opened at Batavia (Jakarta) in 1925, the same year as in Bombay, India.

On November 15, 1931, electrification of the meter gauge track between Madras Beach and Tambaram Sothern part of India)was inaugurated (1.5kV DC). After that the only electrification project undertaken was Borivili - Virar, finished in 1936. For mainline traffic, GIPR undertook electrification of the Karjat-Pune and Kasara-Igatpuri sections because it was realized that the heavy traffic to and from Bombay would be suitable for electric haulage.

Following this there was a long gap, and the next electrification project started only 1953-54, in the Calcutta area, using 3kV DC traction. At this time, the idea of **mainline electrification (Howrah-Mughalsarai) was seriously mooted.** Support for 25kV AC traction was also growing at about this time, especially after some trials of AC locos from SNCF, and studies that concluded that the **single-phase load from electric traction would not seriously unbalance the 3-phase regional grids**.

So the Calcutta area electrification was done keeping in mind the eventual migration to 25kV AC system, in terms of the technical requirements (insulator specifications, etc.). **The first 25kV AC electrified section was Burdwan-Mughalsarai, completed in 1957**, followed by the Tatanagar-Rourkela section on the Howrah-Bombay route. The first actual train run (apart from trial runs) using 25kV AC was on December 15, 1959, on the Kendposi-Rajkharswan section (SER). Howrah-Gaya was electrified by about 1960. Electrification till Kanpur on the Howrah-Delhi route was done by about 1972, and the entire Howrah-Delhi route was electrified on August 5, 1976. The Bombay-Delhi route was electrified by February 1, 1988.

Through the 1960s and early 1970s numerous studies were commissioned to investigate the question of which of diesel or electric traction was really more economical and better in the long run for IR. Most of these leaned towards electrification, especially for high-traffic sections. The rise in oil prices in the mid-1970s tilted the argument further **in favor of electric traction as electricity generation in most of India is hydroelectric or coal-based**. India took the plunge from DC to AC electric traction in the mid-1950s, as mentioned above. Since French developments led the field, the AC locomotives supplied at first (from SNCF) followed that country's practice, whether built in India or France. These were the eight-wheeled WAM-1 locomotives that are still in operation in some places.

The first train to be hauled by an electric locomotive from Delhi Junction was the Assam Mail. Bombay-Delhi (WR) route was fully electrified by Dec. 1987. The CR route was fully electrified by June 1990, when the Bhusaval - Itarsi section was electrified.

The 2 * 25kV AC system (see below) began to be put in place in the 1990s; the first regular service using this system was between Bina and Katni (CR) on January 16, 1995. This was later extended to Bishrampur.

With the BG conversion between Tambaram and Madras Beach complete (12/04), the original1.5kV DC electrification was converted to the 25kV AC system.

After a period of about 25 years of aggressive electrification, now IR has most of the busy routes of its network electrified, and this has resulted in about 70% of the traffic being hauled by electric traction. Recently, IR has decided to slow down the pace of electrification -- about 2600km of routes are scheduled to be electrified in the next 10 years, compared to 5100km in the past 10 years. The focus will be on the busiest sections for electrification.

2.1 Electric traction voltages

In India, Electric Traction Voltages used are 1.5kV DC and 25kV AC for mainline trains. The1.5kV DC overhead system (negative earth, positive catenary) is used around Bombay (This includes Mumbai CST - Kalyan, Kalyan - Pune, Kalyan - Igatpuri, Mumbai CST -Belapur - Panvel, and Churchgate - Virar). There are plans to change this to 25kV AC by 2008. In preparation for this, BHEL has been retrofitting some EMUs with AC drives to allow them to operate with both DC and AC traction as the system conversion proceeds. The Madras suburban routes (Madras-Tambaram in the '60s, extended later to Villupuram) used to be 1.5kV DC until about 1967, when it was converted to 25kV AC (all overhead catenary supply).

The 25kV AC system with overhead supply from a catenary is used throughout the rest of the country. The WCAM series of **locomotives are designed** to operate with **both DC and AC traction** as they move towards or away from the Bombay DC section. The new [2003] AC-DC EMU rakes used in Mumbai are also designed to operate with both DC and AC traction as the Bombay area switches over to the 25kV AC system. The Calcutta Metro uses 750V DC traction with a third-rail mechanism for delivering the electricity to the EMUs.

The Calcutta trams use 550V DC with an overhead catenary system with underground return conductors. The catenary is at a negative potential.

The Delhi Metro uses 25kV AC overhead traction with a catenary system on the ground-level and elevated routes, and uses a rather unusual 'rigid catenary' or overhead power rail in the underground tunnel sections (Line 2).

2.2 Electric traction systems

In overhead electrification *systems* (OHE), the supply of electricity is through an overhead system of suspended cables known as the **catenary**. A **contact wire** or contact cable actually carries the electricity; it is suspended from or attached to other cables above it which ensure that the contact cable is at a uniform height and in the right position. In the following the term catenary is loosely used even when talking about the contact wire.

The loco uses a **pantograph**, a metal structure which can be raised or lowered, to make contact with the overhead contact cable and draw electricity from it to power its motors. (Usually it goes first through a transformer and not directly to the motors.) The pantograph has one or two **blades**, **shoes** or **collector pans** that actually slide against the contact wire. The DC pantographs generally have two shoes, while the AC pantographs have one shoe, owing to the higher current carried by the DC pantograph.The WCAM series of dual-voltage locos have one DC pantograph and one AC pantograph each, but either can be used as a backup for the other traction supply if needed. The new AC-DC EMU on WR uses a single arm pantograph with twin blades.

The pantograph structure may be in the form of a single arm a single open bent angle ('>') or in a diamond (rhombus) form ('<>'). (Other types are not generally used on IR.) The diamond form was more common for the DC locos. Newer locos almost always have the single armpantographs. The single arm types are generally oriented with the bend of the pantograph pointing forwards (in the direction of motion) although this is not a strict rule and locos exist with pantographs in both orientations. Compressed air is used to raise the pantograph from its resting position to the raised position where its shoes touch the contact wire.

The return path for the electricity is through the body of the loco and the wheels to the tracks, which are electrically grounded. (Ground connections are provided from the rails at periodic intervals.) The return current therefore flows through the rails and also partly through the earth beneath and along it. Bonding cables or bonding strips are provided at rail joints (connecting the rails on either side of a fish platedjoint) to ensure continuity of return current flow in the rails (in case the joint is not conductive because of dirt, rust, and so on, and also to allow permanent way operations that involve loosening the fishplates). Earthing cables and earth bond conductors are provided periodically to keep the rails firmly connected to earth and at earth potential and therefore prevent them from developing a floating potential or step voltage that may be hazardous.

Modern electric locos have some fairly sophisticated electronic circuitry to control the motors depending on the speed, load, etc., often after first converting the incoming 25kV AC supply to an internal AC supply with more precisely controlled frequency and phase characteristics, to drive AC motors. Some AC locos (WAG-4, WAM-4) have DC motors, instead. Some AC locos (WAP-5 and WAG-9, both designs from ABB) generate 3-phase AC internally using a thyristor converter system; this 3-phase supply is then used to power asynchronous AC motors. (3-phase AC motors are somewhat more efficient, and can generate higher starting torque.)

The high-voltage systems of adjacent cars are not connected together in the new AC-DC EMUs, so a rake of these can go through a transition in the OHE power supply (where one car is on the AC section, another may be in a neutral section, and a third is in the DC section, for instance) without having to coordinate raising or lowering pantographs among all of them.

In **3rd-rail** systems, electricity is supplied through a thick conductor (the third rail) running along the track; the loco has a **shoe**which maintains sliding contact with it while the train is in motion, to draw current from it. Third-rail traction is seen only in the Calcutta Metro in India. 3rd-rail systems are usually DC systems at much lower voltages (500V-750V or so).

DC System: In DC systems with overhead catenary, the basic principle is the same, with the catenary being supplied electricity at 1.5kV DC. Usually (especially for EMUs) the current from the catenary goes directly to the motors. A DC loco may however convert the DC supply to AC internally using inverters or a motor-generator combination which then drives AC motors.

The generally lower supply voltage of DC systems implies that the currents drawn from the OHE are correspondingly higher. This results in some difficulties, among them the need to use thicker and heavier contact wires and pantographs and to keep the pantograph pressed more firmly against the contact wire causing more wear and tear.

Single system (AC): The overhead catenary is fed electricity at 25kV AC (single-phase) from **feeding posts**which are positioned at frequent intervals alongside the track. The feeding posts themselves are supplied single-phase power from substations placed 35-60km apart along the route. The substations are spaced closer (down to 10-20km) in areas where there is high load / high traffic (These substations in turn are fed electricity at 132kV AC or so from the regional grids operated by state electricity authorities.) A Remote Control Centre, usually close to the divisional traffic control office, has facilities for controlling the power supply to different sections of the catenaries fed by several substations in the area.

2.3 Electrification - Circuit Diagrams

Shown below are three schematic circuit diagrams for electrification systems used on IR. These show the power flow from the 25kV AC catenary through the locomotive.

- Figure1 (a)shows a simple feeding system. Catenary current Ic is returned as rail current I_R and earth currents I_E.
- Figure1 (b)shows the use of booster transformers to force return current through a separate return conductor instead of through the rails or earth. Insulated rail joints ensure that currents flow in the rails only in occupied track sections. Inductive interference is reduced since the return wire is close to and parallel to the catenary.
- The third Figure1(c) shows an auto-transformer system (also known as the 3-wire system or 2x25kV system). Inductive interference is reduced as the negative phase feeder and catenary carry equal but opposite currents and isclose to each other and parallel. The supply voltage to the locos can be kept close to the 25kV figure by tap changers on the autotransformers. (Note: In the autotransformer case the currents drawn do not have to be

symmetric across the autotransformers on the left and right of the loco -- they can vary, as long the currents add up to half the current drawn by the loco.)

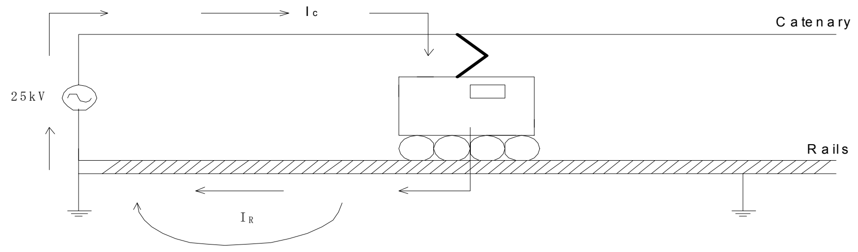

Fig.1 (a) Simple catenary feeding system

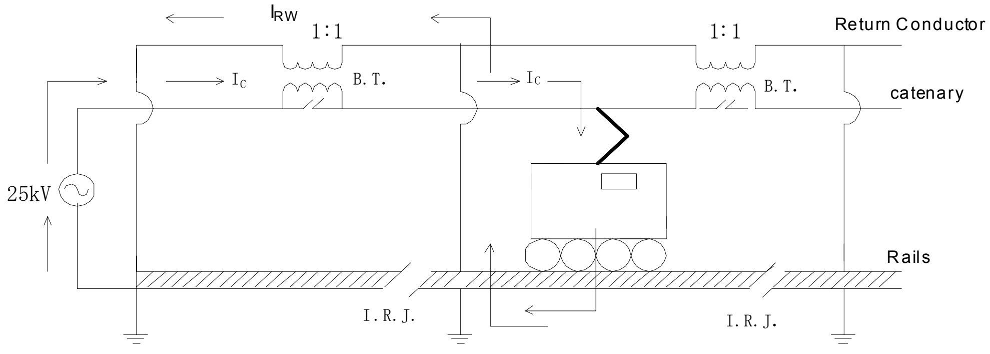

Fig.1 (b) Booster Transformer feeding system with return conductor & Insulated Rail Joints

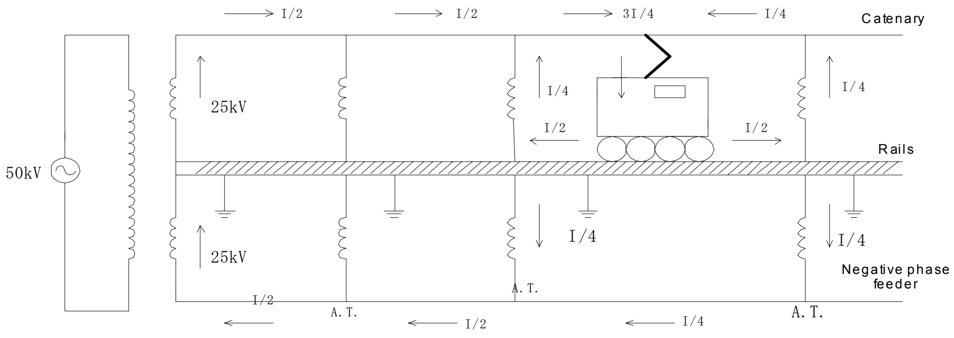

Fig.1(c) Autotransformer feeding system (2x25 KV)

Booster Transformer (BT) System: In the simple ACsystem described above, there can be severe inductive interference in telecom lines and other equipment because of the large loop area between the catenary and the rails which carry the return current (I_R in the top diagram in the schematics). Some of the return current also flows in the earth (shown as $I_E$in the top diagram), causing conductive interference and corrosion problems in buried cables, pipes, etc. Such earth currents are higher if the conductive path in the rails is degraded because of rail joint problems.

Figure 1(b)is a schematic for the booster transformer (BT) feeding system. There is now a return conductor, a wire that is close to and parallel to the catenary wire. The return conductor is connected to the rails (and earthed) as shown. Periodically, there are breaks in the catenary where the supply current is forced to flow through one winding of a booster transformer (marked B.T.); the other winding is in series with the return conductor. The 1:1 turn ratio of the BT means that the current in the catenary (Ic) will be very nearly the same as the current in the return conductor (Irc). The current that flows through the loco goes to the rails but then up through a connecting wire to the return conductor and through it back to the substation.

Insulated rail joints (marked I.R.J.) are also provided -- this ensures that current flows in the rails only in the particular section where the loco is present. At all other places, the inductive interference from the catenary current is nearly cancelled by that from the return current, thus minimizing the interference effects. The problem of stray earth currents is also reduced.

One of the disadvantages in this system is that as a loco passes a booster transformer, there is a momentary interruption in thesupply (because of the break in the catenary) with the attendant problems of arcing and transients on the line, as well as radio frequency interference.

In recent years, as much telecommunication cabling has been moved away from railway lines or re-laid underground, interference from the electric traction system is not as much of a problem as it used to be in the past, and therefore in many cases the booster transformers and return conductors have been removed and the traction system has been reverted to the plain single-wire system.

Autotransformer (AT) System / 2 x 25kV System / 'Dual' System: Both the simple AC feeding scheme and the booster transformer scheme suffer from voltage drops along the length of the catenary locos may see severely reduced voltages (by 5kV or more) at points far from the substation. Figure 1(c) is a schematic for an autotransformer (AT) feeding system, which is intended to address this voltage drop problem. The current flow is more complex here. A 50kV supply from the substation is split with a three-winding transformer into a dual 25kV supply (also sometimes called a '2-phase' supply). Between the catenary and the rails is 25kV of voltage. Between the rails and the other phase is also 25kV of voltage (but always instantaneously opposed in sense 180 degrees out of phase). This other phase (sometimes called 'negative' phase which is a bit misleading since there's no positive or negative here, as it is AC supply) is carried on a feeder wire parallel to the catenary.

There are autotransformers (marked A.T.) provided periodically as shown. These are usually tap-changing transformers that can adjust their turns ratio as required the aim is to keep the voltage drop between the rails and the catenary always at 25kV as far as possible. But neglecting voltage drops, the turns ratio of these autotransformers is essentially 1:1 between catenary and rails and rails and feeder.

Consider the loco as shown, drawing a load current I. Each phase (catenary and feeder) carries half of this. The currents split and merge as shown in the section just where the loco is. The autotransformer action forces equal currents to flow between the rails and the catenary and between the rails and the feeder in all cases. Note that the rails carry less than the full load current in each direction away from the loco, and that's the only section where the rails carry current. (The rails are shown carrying equal currents I/2 in each direction away from the loco, but that's a simplification they do not have to be symmetric in that way as long as the two currents add up to load current drawn by the loco.) Note further that the full load current does not flow in the catenary anywhere either. Also, in all the other sections except where the loco is, the catenary and feeder carry equal but opposite currents, providing for the cancellation of inductive interference as in the BT system. The net effect is that in the unoccupied sections the inductive interference is as low as with the BT system, and in the occupied section it is lower than in the BT system. At the same time, the voltage drop problem is eliminated.

Further, there are no unnecessary breaks in the catenary, reducing radio frequency interference and transients on the power system. The reduced currents and 50kV supply also mean that substations can also be farther apart. So far the 2*25kV system is in use onlyabout 10% of all of IR's electrified routes. A couple of sections that had the 2x25kV in the past have also recently been reverted back to the simpler standard system. The dual system corresponds to what is called the **3wire system** (with transmission line) in other railways.

Substations: The substation receives High Tension supply from the regional grid is transformed to a voltage suitable for use for the railways, and fed to the various sections of the catenaries. An AC substation is generally fed 3phase power, and the phases are split out so that a given catenary section gets only one phase supplied to it. Both AC and DC systems have transformer sections to convert the voltage to a suitable level, and also capacitor banks (sometimes along with thyristor switching circuits) to improve the power factor. The transformers are of 20 30 MVA capacity. DC substations in addition also have rectifying units to convert the AC to DC. The Traction Power Controller (TPC) is the official authority for monitoring the part of the system served by the substation and can switch the supply to the OHE on or off, change configurations of transformer taps (after shutting down the system), control the capacitor banks to adjust power factor and voltage etc.

Atypical traction power supply configuration, from the 3-phase regional high-voltage grid through the traction transformers and the sectioning and sub sectioning and paralleling posts to the 25kV AC catenary is given in Fig.2.

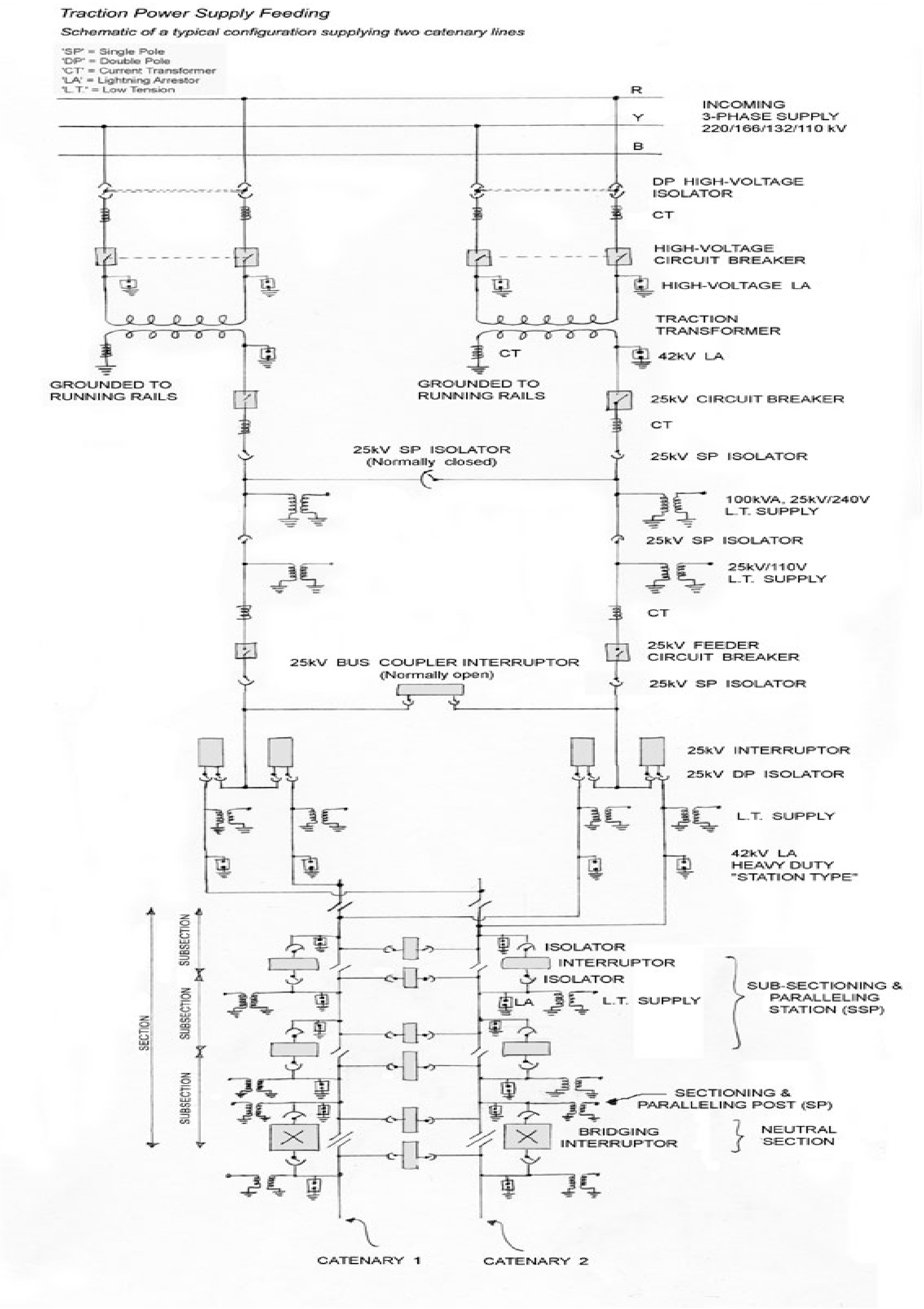

Fig.2 Regional Grid Connectivity

Substations are generally closer together on DC systems than AC systems, because the latter allow the use of higher voltages and lower currents drawn, which in turn reduces voltage drops.

Transmission voltage: Power is transmitted to the electrical substations at 750kV, 220kV, 132kV, or 110kV and then stepped down as required to 25kV or 50kV. The power from the grid is usually in the form of 3phase power.

Catenary voltage: In practice, the catenary voltage in the 25kV AC system can vary from something like 18kV to over 30kV because of poor regulation at the substation or incorrect configurations of the transformers, etc. Most locos are designed to handle a certain range of catenary voltages, although of course the operation may be less than optimal at voltages far from the norm.

Electrical Parameters of AC OHE system

Traction Supply Voltage:
Nominal Voltage: 25kV
Permissible Limits: 19.9kV to 27.5kV (17.5kV for Mumbai EMUs)

Traction Supply Frequency:
Nominal: 50Hz
Permissible Limits: 48.5Hz - 51.5Hz

Loop impedance of OHE with earth and rail return:]
Single line: 0.41∠70°?/km
Double line: 0.24∠70°?/km

Loop impedance with the booster transformer / return conductor:
Single line: 0.70∠70°?/km
Double line: 0.43∠70°?/km

Traction Transformer Rating: 13.5MVA
Traction Transformer Resistance: 0.179 ohm
Traction Transformer Reactance: 5.49 ohm

Harmonics in traction current with silicon diode locomotives:
3rd Harmonic - 150Hz: 38.5% at 142A, 11.5% at 480A
5th Harmonic - 250Hz: 14.35% at 142A, 5.48% at 480A
7th Harmonic - 350Hz: 15.0% at 142A, 2.0% at 480A

Average Power Factor: 0.7-0.8
(this was before 3-phase locos were introduced in large numbers)

Catenaries: IR uses catenaries of the constant-tension type. At one end of each section of the catenary the cable goes over a pulley and is terminated by a hanging weight. The pulley and weight combination ensures that the catenary cable maintains the same tension regardless of the ambient temperature and the consequent expansion or contraction of the cable. This avoids problems with the catenary sagging too much in hot weather, or, if the tension is too high, snapping in cold weather.

Further, it is important that the tension be within certain precise bounds for mechanical reasons: the moving pantograph creates a shock wave in the catenary that travels along the cable; its speed is determined by the tension in the catenary, and if it is less than the speed of the pantograph, the cable will be prone to buckling and snapping. The pressure of the pantograph pan against the contact wire is usually around 6.5kg/cm^2 on IR. The equivalent copper cross-section of the catenary is usually about 157 to 165 sq. mm. (65 sq. mm. stranded copper-cadmium catenary and 107 sq. mm. grooved copper contact wire). On a single-track section, this allows a current of up to 600A to be drawn from the catenary without raising its temperature to more than about 85°C, which is the safe upper limit to avoid risks of fire, equipment failure, etc., and to maintain the physical properties of the catenary within acceptable bounds. On the Waltair-Kirandul section which sees extremely heavy ore traffic, and some other busier sections catenary equivalent cross-sections are up to 200 sq. mm, whereas loops, spurs, sidings, etc. often have lower-capacity catenaries with equivalent copper cross-sections of 107 sq. mm.

DC traction sections have much higher equivalent cross-sections because of the higher current drawn (as the voltage is about 1/16 that of AC sections, the current is correspondingly higher, necessitating a total catenary cross-section about 4 times that used on AC sections). Typically, the equivalent cross-section for DC catenaries is about 645 sq. mm (323 sq. mm primary catenary cable, 129 sq. mm auxiliary catenary, and 193 sq. mm contact wire).

As mentioned earlier, the catenary in fact consists of more than one cable; the one that actually touches the pantograph and carries the current is the **contact wire**. The contact wire may be suspended directly from the cantilever arms from the support posts (this is not common, and is only found on low-speed sections and turnouts). More often, the contact wire is suspended from another wire called the **messenger wire**. The messenger is the one that assumes the typical catenary (hyperbolic cosine) curve shape. The contact wire is suspended from the messenger by vertical **risers** or **spacers**. A third wire, the **auxiliary cable**may appear between the messenger and the contact wire although this design is rare in India. The contact wire is usually grooved on the sides, so that it can be gripped firmly from the sides without creating any discontinuity on the lower surface where the pantograph rubs against it. It is usually made of hard-drawn copper, although sometimes copper alloys have been used. The other part -- the catenary cable -- is made up of multiple strands of copper, or more often, a copper-cadmium alloy. In 1990, IR experimented with installing aluminium contact wire catenary on a 260km section in SER (Durg-Nagpur). This proved to be unworkable because there were too many defects caused by oxidation and mechanical failure (strand breakage) in the wire, and the aluminium cables were replaced by standard copper-cadmium wires by 1998. The messenger wire is usually of an alloy chosen more for its mechanical properties as it does not need to conduct the traction current. WR tends to use 2 current-carrying cables and more closely-spaced substations to power its 1.5kV DC catenaries; CR tends to use 3 current-carrying cables and substations that are farther apart.

Catenary Height: The contact wire is generally at about 5.5m from the rail level. The minimum height is around 4.8m (e.g., under bridges or overpasses, etc.). In yards, in sheds or lines leading up to sheds, etc., the catenary contact wire may be higher; 5.8m is a typical height.

At the end of each section of catenary, a new section begins, with the old and new catenaries running in parallel for a short distance. On BG routes, this switch from one catenary to another usually happens over a length corresponding to 4 catenary masts, with the old and new catenaries overlapping (running parallel) for about 50m. On MG, this is usually accomplished over a length corresponding to 3 catenary masts, with one catenary taking off immediately after the point where the other stops.

When successive sections of the AC catenary are supplied by different phases from the 3-phase power grid, there is a short, electrically neutral (un-energized) section (**dead zone** or **neutral section**) of catenary that comes between them. The loco has to coast through this 'phase break' with a brief interruption in the supply of power. Sometimes different sections of the catenary are connected to different phases at different times and the neutral sections may be a **switched neutral section**. (The term also refers to neutral sections at AC-DC switchover points where the neutral section can be switched to either the AC or the DC supply, and is also known as the **dynamic neutral section**.)

In DC catenaries, there are similar breaks (power gaps) with neutral sections at points where adjacent sections of catenary are supplied by different substations. Neutral sections used to be quite long (41m was a common length) but now many neutral sections corresponding to phase breaks in the AC power supply are as short as 5m. Some locomotives are also being provided with modifications to keep their headlights and some auxiliary equipment turned on while traversing the neutral section.

2.4 Control and Monitoring

A Remote Control Center (RCC) is located at or near the divisional traffic control centre. The RCC has the control and monitoring equipment for the electric traction in the areas controlled by the traffic control centre. Prior to 1980, IR used an electro-mechanical control system, Frequency Modulated Voice Frequency Telegraph (FMVFT). These are still in use in some places. Since 1980, IR has been installing a microprocessor-based system called SCADA (Supervisory Remote Control and Data Acquisition System) for remote control of electric substations and switchgear. A central SCADA facility (the division control centre) can control a region extending to about 200-300km around it. SCADA allows remote monitoring of electrical parameters (voltage, current, power factor, etc.) in real time and remote operation of switchgear, as well as automatic fault detection and isolation, allowing better control of maximum demand, trouble-shooting, etc. SCADA replaces an older system that used electro-mechanical remote control apparatus.

3. Conclusions

A history of Indian Railway electrification, future plan has been dealt in detail. All the three types of traction electrification systems are explained. Further, overhead electrification *system's* electric parameters are outlined. In-depth details regarding catenary and pantograph have been presented.

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