J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*

GROUND TRANSPORTATION SYSTEMS

Ground transportation systems (*GTS*s) move people and goods over special ground or underground routes. A *GTS* includes not only the means of transport, but also the entire infrastructure necessary for providing it.

The great variety of *GTS*s in use may be classified as follows:

- Road systems (buses, guided buses, trolleybuses, automobiles)
- Rail systems (railroads, street cars, subways, light rail)
- nonconventional systems (maglev, people movers, automatic guided transport, monorails, vehicles with gyroscopes, industrial transport).

This paper is concerned with electrical means of ground transport, so the main focus is on the operation of transport systems with electrically propelled vehicles—*electric vehicles* (*EV*s). When power to vehicles is delivered via a special power supply network, the system is called an *electrified (network) transport system;* when the source of energy is installed in the vehicle, the system is called *autonomous.* Electrified transport systems can be divided according to the type of power supply: ac or dc, as shown in Tables 1 and 2. EVs supplied by an electric transport power supply system (*ETPSS*) collect electrical energy from an *overhead catenary* (railroads, light rail, streetcars [one pole contact wire; see Fig. 1], trolleybuses [two separated negative and positive overhead wires; see Fig. 2(a)]) or from a *third rail* (railroads in the UK and Berlin, subways), mounted on isolators, through a shoe-type current collector [Fig. 2(b)] placed beside or below the EV. When energy is delivered to a guideway rather than to the EV (as in maglev), no catenary is required (Fig. 3). Nonconventional systems are usually electrified with a special power supply network.

Autonomous vehicles are powered by their own source of electrical energy: electrochemical batteries, diesel generators, gas turbine generators, or fuel cells installed onboard.

Drive systems for conventional electrical transport are equipped with dc series (usually) or compound motors, ac three-phase asynchronous or synchronous motors, ac single-phase commutator motors, or ripple current motors; some nonconventional systems apply linear induction (asynchronous) or synchronous motors (maglev or subway).

According to the type of service, transport systems can be distinguished as follows: *mainline* (long-distance, intercity: high-speed railroad, upgraded conventional railroad, maglev), *regional, suburban, urban* (streetcars, light rail, subways, trolleybuses), and *local* (people movers, monorail).

Railroads

The most widespread transport systems in the world are railroads using double-rail track: narrow-gauge (1000 mm to 1067 mm, as in Japan, Taiwan, Central America, and South Africa), standard (1435 mm) or wide-gauge (1524 mm in the former Soviet Union, Finland, and Mongolia; 1668 mm in Spain, Portugal, and South America; 1600 mm in Ireland). The lower motion resistance on rails than on roads allows hauling heavy freight trains

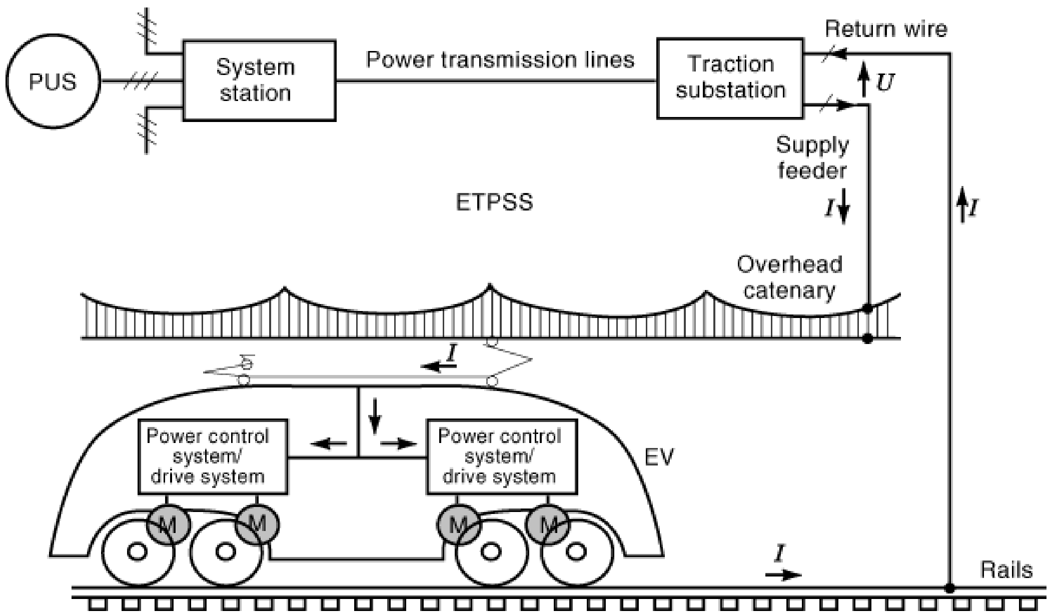

Fig. 1. Basic scheme of electrified ground transport power supply system with rail electric vehicles supplied by overhead catenary.

(with masses of 2000 tonnes to 6000 tonnes and in some cases over 10,000 tonnes), but requires significant expense for the technical infrastructure (track, fixed installation of power supply system, signaling and control systems).

High-Speed Railroads

Because roads are overcrowded and railroads exceed other means of transport in energy efficiency, environmental friendliness, and comfort of service, there has been new interest in electrified rail transport. In order to compete with air transport over distances on the order of hundreds of kilometers, *high-speed railroads* (*HSR*s) are being developed (Table 3). *HSR*s trains in Europe are usually composed of a set of cars, with powered cars at both ends. International interoperability of trains in Europe requires operation under different power supply systems. In addition, TGV-type trains, the French equivalent of *HSR*s, are in service in Spain (AVE), and Trans-European Euro-star multisystem trains use TGV technology. HSR projects are ongoing as well in Russia, the United States, South Korea, Canada, and Taiwan. Difficulties with power delivery from overhead contact lines to vehicles limit the maximum speed of such rail systems to 350 km/h. Thus, maglev systems are being constructed as the next generation of high-speed ground transport systems.

Maglev

Maglev (magnetic levitation) is technologically the most advanced transportation concept. It uses magnetic forces to suspend the vehicle over the guideway and for lateral guiding. (Fig. 3), and a *linear induction motor* to drive the vehicle. The suspension may be *electromagnetic* (as in the TRANSRAPID test line in Germany) or

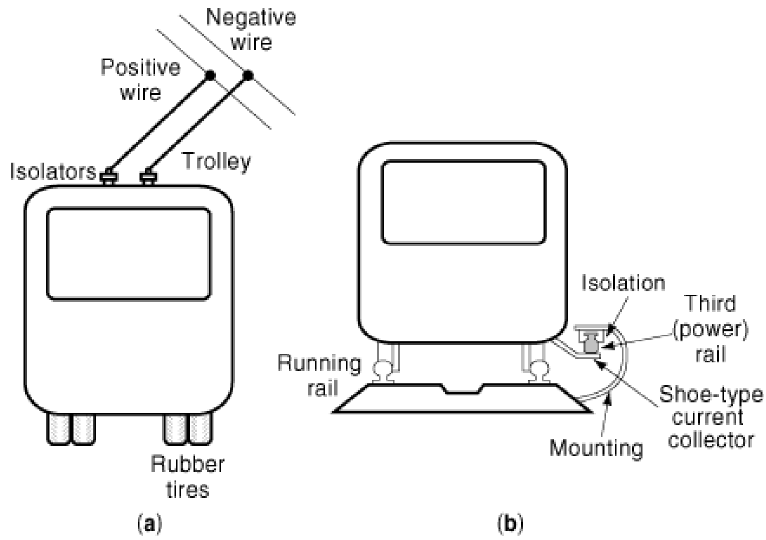

Fig. 2. (a) Trolleybus two-pole catenary; (b) third-rail power supply.

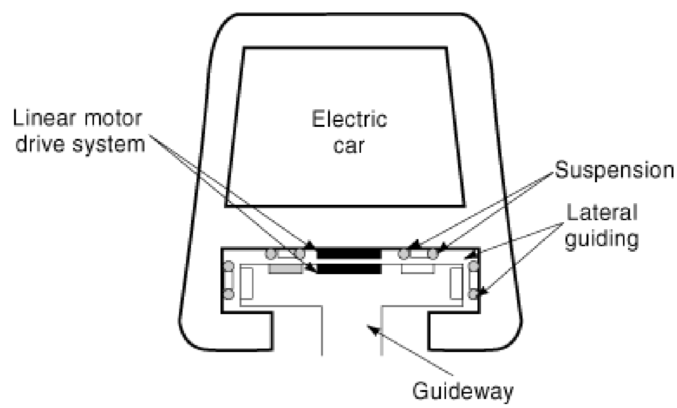

Fig. 3. A scheme for a maglev car.

electrodynamic (as in the Yamanashi and Miyazaki test lines in Japan), and may make use of superconducting materials. This system has following advantages over the conventional ones:

- No adhesion needed for drive or for braking, the resistance to motion being solely aerodynamic, so that higher gradients and sharper curves can be used
- Maintenance of horizontal (lateral) position by magnetic forces
- No contact vibration and less noise, as there are no rolling wheels or rails
- Minimum maintenance
- High safety and reliability at speeds up to 500 km/h
- No catenary, as power is delivered to the guideway.

Table 1. AC Traction Systems[a]

Frequency (Hz)	Voltage (kV)	Countries
25	6.5	Austria
	11	United States
50	20	Japan
	25[b]	Bulgaria, People's Republic of China, Czech Republic, Slovakia, Denmark, Finland, France, UK, Hungary, India, Japan, Luxembourg, New Zealand, Pakistan, Portugal, Romania, South Africa, Spain, Turkey, Yugoslavia, Zaire, Zimbabwe, countries of former Soviet Union
	50[b]	South Africa
60	20	Japan
	25[b]	Japan, South Korea
	50[b]	Canada, United States
$16\frac{2}{3}$	11	Switzerland
	15[b]	Austria, Germany, Norway, Sweden, Switzerland

[a] Railroads only.
[b] Suggested for newly electrified lines.

The primary energy consumption per passenger kilometer (with service speed over 400 km/h) in slightly higher than for automobiles (which have a quarter the speed), but only half that for airplanes over the same distance (1). The practical maximum speed for service is 500 km/h, on account of increasing aerodynamic resistance. The first commercial maglev train has been successfully operating at low speed for 11 years on a 600 m long track (a 90 s journey) at Birmingham Airport.

Conventional Railroads

Some of the high technology developed for *HSR*s is being transferred to conventional railroads, which, though they do not reach very high speed, can apply ac motors with power electronic converters and braking energy regeneration to improve the quality of service, lower the cost of maintenance, energy consumption, and environmental impact, and increase the speed. The flexibility of multisystem power supply for trains (composed of locomotives with cars or of multiple traction units) allows one to use the same electrical vehicles on railroad lines and in cities on light-rail lines (as in Karlsruhe, Germany) or even on nonelectrified sections of railroads (when vehicles are additionally equipped with diesel generators or storage batteries).

Urban Transport Systems

Electrified transport started at the end of the nineteenth century in towns, and is now enjoying a significant comeback in cities overcrowded with cars and buses causing environmental pollution. Subways, light-rail systems (on dedicated track on bridges and in excavations avoiding level crossings with roads), and modern

Table 2. DC Traction Systems

Type (Hz)	Voltage (kV)	Countries
Railroad	3	Algeria, Belgium, Brazil, Chile, Czech Republic, Italy, Luxembourg, Morocco, Poland, Slovakia, South Africa, Spain, United States, countries of former Soviet Union, Yugoslavia
	1.5	Australia, Czech Republic, Denmark, France, UK, Netherlands, India, Japan, New Zealand, Portugal, Spain, United States
	0.63, 0,75, 1.2	UK, Spain
Light rail[a]	1.5	Ireland
Subway, light rail[a]	0.7–0.9	
Streetcars, trolleybuses[a]	0.6	
Industrial transport, mine railroads	<0.6	

[a] Suggested for newly electrified lines.

streetcars (separated from road traffic on streets, with traffic-light priority) yield the highest traffic capacity (Table 4). Low-floor, easy-access streetcars allow one to use traditional routes and drive smoothly into city centers. Nonconventional solutions include people-movers, mini-trams, and fully automated guided transport (Lille, France, 1983; Docklands, London, 1987; SkyTrain, Vancouver, 1986; Automated Skyway Express, Jacksonville, FL, 1992) on special guideways or monorails, used over short distances in areas where efficient passenger transport is in heavy demand (as in airports and at expositions) and needs to be integrated effectively with other transport modes (such as the Chiba Urban Monorail System in Japan). In order to lower the cost of the infrastructure in less-populated areas, trolleybuses are used, and tests are being performed on optically guided hybrids such as diesel–electric buses or minitrams equipped with batteries or gyroscopes, fed from low-voltage power points at stops. The use of *linear motors* in rail subways in Tokyo and Osaka, Japan, has allowed decreased tunnel diameter and lower capital costs.

The choice of an urban transport system depends on the required transport capacity T_C (Table 4), which may be calculated using the following formulae:

$$T_c = \frac{P_c n v}{d} = \frac{P_c n}{h} \qquad (1)$$

where

T_e = transport capacity in one direction [passengers/h]
P_v = average capacity of a car [passengers]
n = number of cars in a train

Table 3. High Speed Railroads in the World

Train	Country	Type of Track	Maximum speed reached (km/h)	Maximum service speed (km/h)	Power supply system
TGV	France	Dedicated; min. radius of curvature 8000 m	515.3 (1990)	300 (350 in 1998)	Ac 25 kV 50 Hz
Shinkansen	Japan	Dedicated; min. radius of curvature 6000 m	325.7	270	Ac 25 kV 60 Hz
ICE	Germany	Dedicated; min. radius of curvature 6000 m	406.9 (1988)	280	Ac 15 kV $16\frac{2}{3}$ Hz
Pendolino	Italy	Upgraded existing track (tilting cars)		250	Dc 3 kV
ICC 225	UK	Upgraded existing track		225	Ac 25 kV 50 Hz
X200	Sweden	Upgraded existing track (tilting cars)	275.7 (1993)	200	Ac 15 kV $16\frac{2}{3}$ Hz

v = average service speed [km/h]
h = headway of trains [h]
d = distance between trains [km]

Electric Transport Power Supply Systems

An ETPSS is composed of electric power transmission circuits and fixed installations, which are to deliver energy to EVs from dedicated for *GTS* power stations or public utility systems (*PUS*s). An ETPSS distributes energy as required by the traction system. Specifications include dc or ac, the voltage, and, if ac, the frequency and whether one- or three-phase. The electric circuits of an ETPSS include *power stations* or *transformer stations, power lines, traction substations* (ac or dc), *supply feeders,* and a *traction power network* (supply and return network). A typical scheme of an ETPSS is presented in Fig. 1, and designs of different systems are shown in Fig. 4 (dc system), Fig. 5(a–d) (ac industrial-frequency system) and Fig. 6 (low-frequency 16 $\frac{2}{3}$ Hz or 25 Hz systems). Characteristic parameters of different traction systems are given in Table 5.

Schemes of Traction Power Supply. Power supply schemes of traction systems are divided into feeder sections, which are separated by isolators in the catenary and supplied from the traction substation (*TS*). When one feeder supplies one section one refers to *unilateral supply;* when two feeders from different sides supply a section of catenary, to *bilateral supply.* When sections of catenary for parallel tracks are connected

Table 4. Typical Traffic Parameters of Electrified Urban Transport Systems

Type of system	Frequency[a] (trains/h)	Distances between Stops (km)	Transport Capacity[a] (10^3 passengers/h)	Average speed (km/h)
Streetcar	50–60	0.4–1.5	15	15–20
Modern tram	40	0.8–2.0	20	20–30
Subway	90	0.6–1.5	40	35–45
Rapid light rail	20	0.8–3.0	45	45–55
Suburban railway	12	1.5–5.0	50	55–60

[a] Maximum.

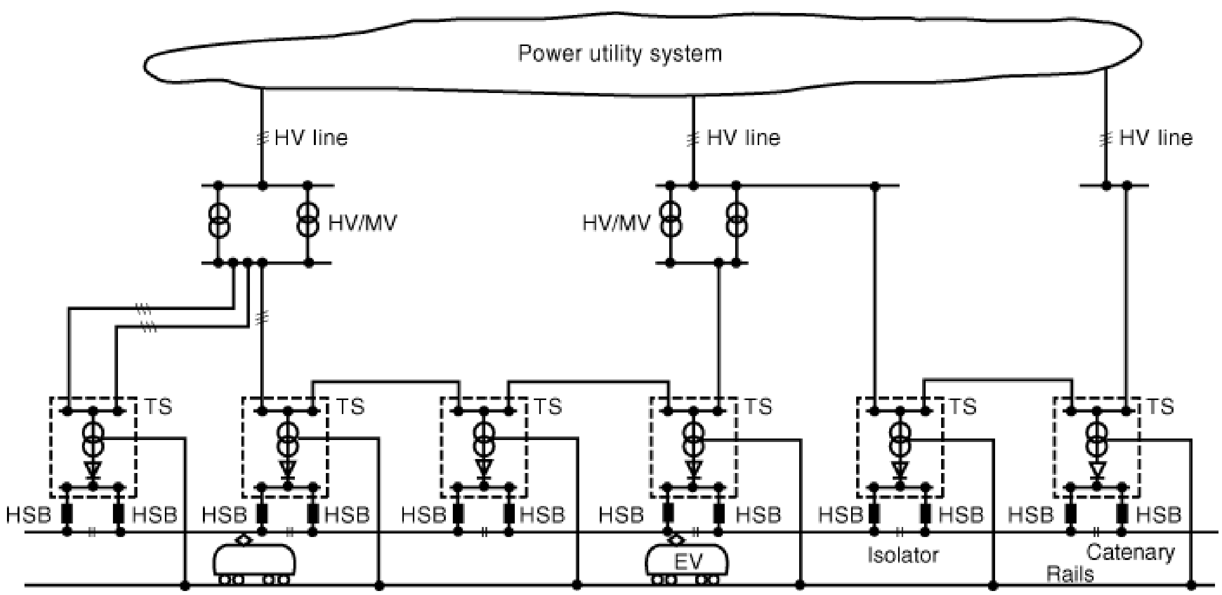

Fig. 4. Dc electrified transport system power supply.

together, this connection is called *track-sectioning equipment* (or parallel connection points); when equipped with high-speed breakers (*HSB*s), the combination is called a *traction sectioning cabin* [Fig. 7(a,b,c)]. Unilateral supply is used on 25 kV 50 Hz ac, 15 kV 16 $\frac{2}{3}$ Hz, and 0.6 kV dc traction systems. Bilateral supply is common within 0.8 kV, 1.5 kV, and 3 kV dc systems, while main railway lines electrified with 3 kV dc utilize bilateral supply with traction sectioning cabins.

The main purposes of bilateral supply with traction sectioning cabins are lowering voltage drops, improving short-circuit protection, sharing current between different feeders, improving flexibility of the power supply, and, in case of a feeder or TS failure, the capability of switching equipment to make rearrangements to maintain power supply through an adjoining feeder or TS.

DC Traction Systems. In a dc traction system (Fig. 4) the ETPSS includes ac power supply lines (high or medium voltage) transmitting power from the power utility system to ac–dc traction substations. Ac

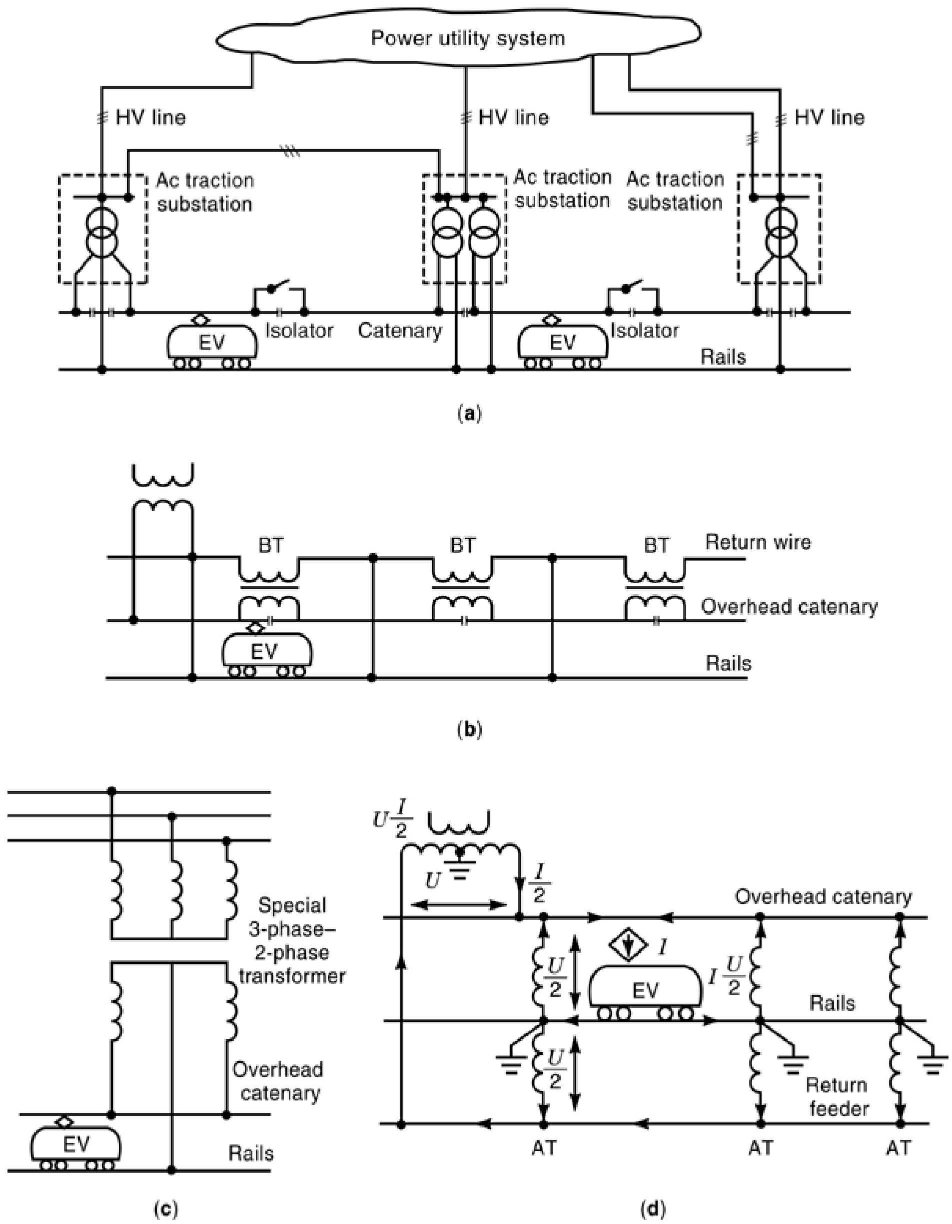

Fig. 5. Ac industrial-frequency electrified transport system: (a) general scheme, (b) with booster transformer, (c) with special three-phase–two-phase transformers, (d) with auto transformer (*AT*).

three-phase power delivered to the TS is then converted to dc power at the required voltage. Mostly 6- or 12-pulse diode rectifiers are used. If voltage control is required (for instance to increase the voltage level under high load or reduce it under no-load conditions), thyristor rectifiers are used, which can also operate as *HSB*s. When EVs are equipped with regenerative braking equipment, the installation of inverting converters in the TS allows transferring excess energy from EV to ETPSSPUS. Dc power is supplied to the traction supply network from dc positive busbars through feeders (cable or overhead) with *HSB*s (short-circuit protective devices) and

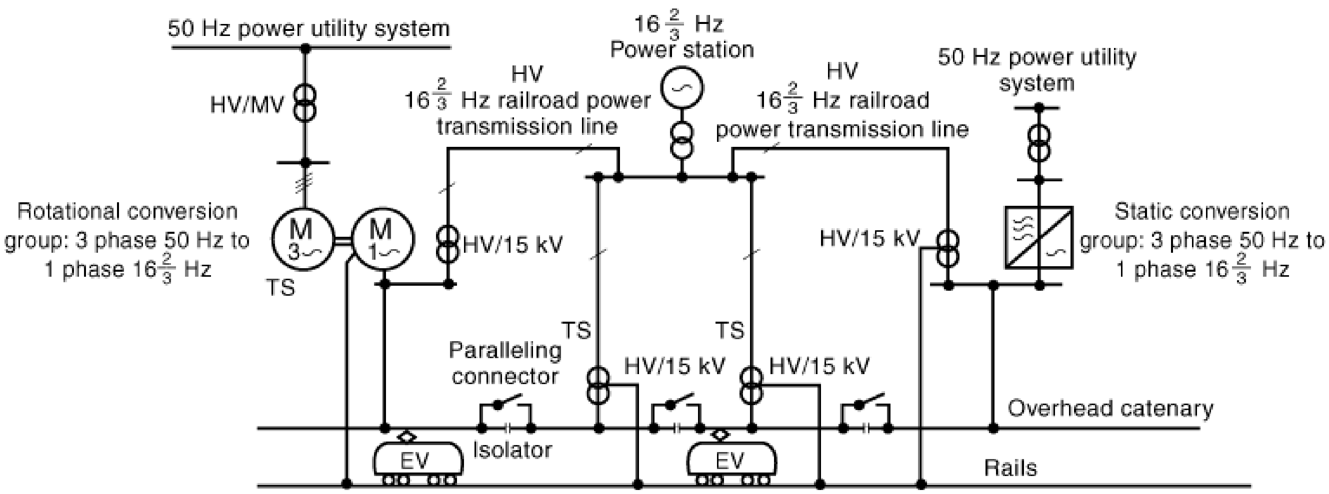

Fig. 6. Ac low-frequency electrified transport system.

Table 5. Typical Parameters of Power Supplies for Electric Traction Systems

Voltage (kV)	Freq. (Hz)	Section Length (km)	Catenary Cu Cross Section (mm^2)	Scheme
0.6	Dc	0.5–2.0	80–190	Unilateral
0.8	Dc	1.0–4.0	Third rail[a]	Bilateral–unilateral
1.5	Dc	10–15	320–440	Bilateral–bilateral[b]
3.0	Dc	12–30	190–610	Bilateral–bilateral[c]
15	$16\frac{2}{3}$	50–70	190–240	Unilateral–bilateral
25	50	60–90	190–240	Unilateral
2 × 25	50	60–120	190–240	Unilateral

[a] Fe or Al.
[b] With section cabins.
[c] With cabins.

switching apparatus, while negative busbars, under normal conditions isolated from the ground (by a spark gap or special grounding equipment) is connected to the rails via return feeders. However, in some systems the polarity is reversed, and the catenary is connected to negative busbars.

Return Network of DC Systems. The return network (*RN*) of a dc power supply is composed of running rails and return feeders. In order to lower the electrical resistance, the rails of the track (for double-track lines, of both tracks) are connected in parallel, with the installation of special *impedance bonds* on sections with track circuits [Fig. 8(a,b)]. In a *fourth-rail* system (as in the London Underground, or when wheels with rubber tires are used to lessen vibration and noise), the running rails are separated from the traction current flow and retu feeders are connected to a fourth rail, which collects return current from the EV. This last approach eliminates stray current outflow from the rails to ground.

Protection of DC Traction Systems. The ETPSS must maintain the power supply with high reliability and must detect and quickly eliminate fault conditions. This accomplished by installing dc *HSB*s to protect every feeder from short circuit (*SC*). An HSB clears the fault in 15 ms to 30 ms, depending on the inductance and resistance of the circuit and the internal tripping time of the HSB. Usually an HSB trips when the

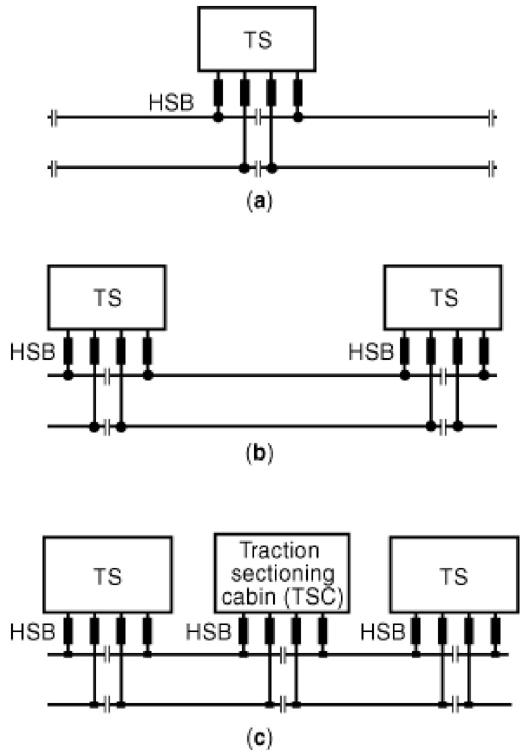

Fig. 7. Schemes for sectioning the catenary of a two-track railroad: (a) unilateral supply from one TS, (b) bilateral supply from two TSs, (c) bilateral supply with traction sectioning cabin.

instantaneous value of the current exceeds the preset value I_s (instantaneous series trip relay). When the SC happens close to the TS, the steady-state current may reach tens of thousands of amperes, which has to be within the switching-off capacity of the HSB. For a distant SC the minimum current I_{SCmin} (which depends on the resistance of the circuit and the TS and the system voltage) may be lower than the maximum load current I_L. In that case it is impossible to set the level of protection I_8 to distinguish between the load and the SC current, as when $I_s > I_L$ (in order not to switch off the load current) one has $I_s > I_{SCmin}$ and the HSB does not clear the distant SC. In the other case, when $I_s > I_{SCmin}$, the SC will be cleared, but load currents $I_L > I_s$ will be switched off, which will cause a traffic disturbance. In case it is impossible to overcome this problem by changes in the supply arrangements (such as shortening the feeder section, switching from unilateral to bilateral supply with interlocking between the adjacent feeder *HSB*s, or decreasing resistance of the supply circuit), a special detector must be used. This differential protection device distinguishes between the instantaneous current load I_L and the SC current I_{sc}. The instantaneous series trip relay responds to di/dt and its duration, or to the change (rise) of current, Δi (Fig. 9), over a certain time; it is possible to set $I_s > I_L > I_{SCmin}$. As most SCs in a traction catenary are temporary, after the HSB switches off the supply from the section, an impedance relay is used to measure the impedance of the faulty section. If the impedance is high enough, the HSB automatically makes a few tries at switching on voltage to the section.

Protection against ground fault is obtained by installing special devices, such as spark gaps or grounding switches, between negative busbars and the ground electrode of the TS. Under normal operating conditions this equipment separates the negative electrode from the ground. In case the voltage between the ground electrode and the negative electrode of the TS exceeds the preset value, the equipment makes a connection between

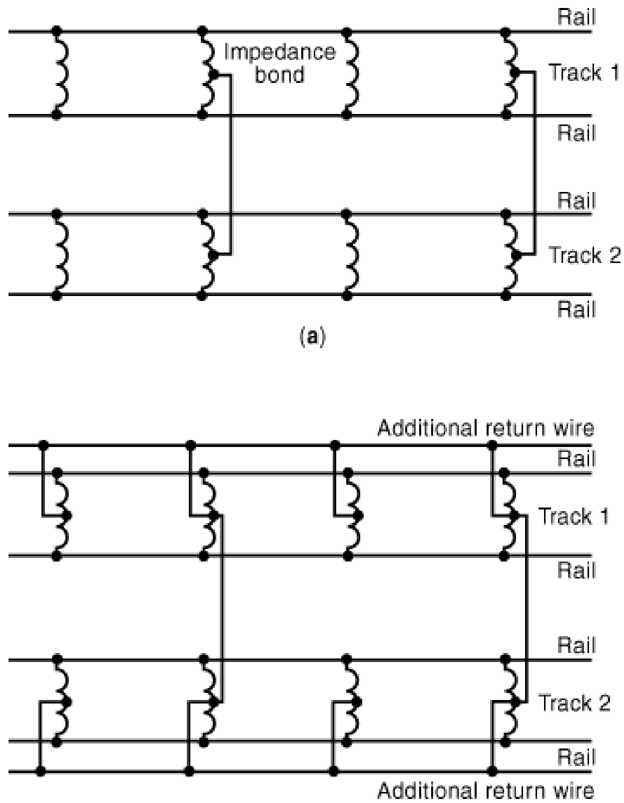

Fig. 8. Parallel connection of rails of a two-track railroad line: (a) using centers of impedance bonds, (b) using additional return wires.

them. If the grounding current flowing through the switch is high enough, then the HSB of the appropriate feeder may clear the fault; otherwise, after a time delay, the special relay trips the ac power switch (time of operation up to 200 ms) of the TS. In order to make the SC from the catenary to the support structures a full SC, they are bonded to the rails [Fig. 20(a)], either individually or in a section group (by a ground wire). Double isolation with the ground wire and individual grounding of support structures may also be used [Fig. 19(b)], but that requires isolation of the foundations from the earth. In case there may be stray currents, special separating devices such as spark gaps or overvoltage contactors (switches) are included in the bonding wire, to connect the ground wire and structures to the rails when the voltage rises above a specified level. Additional protection against SCs of lower level and longer duration is undervoltage protection with a specified voltage–time characteristic. The overhead catenary may additionally be provided with thermal overload protection and lightning protection. The type and the setting of the traction power supply network protection depend on the fixed installation arrangements, local codes of practice, and conditions as well as the characteristics of the operating EV (type of drive system, with or without regenerative braking).

AC Industrial-Frequency Systems. A scheme of a simple single-phase ETPSS with rail return, shown in Fig. 5(a), includes three-phase HV power lines connecting the PUS with the traction TSs. In practice more sophisticated solutions are in common use:

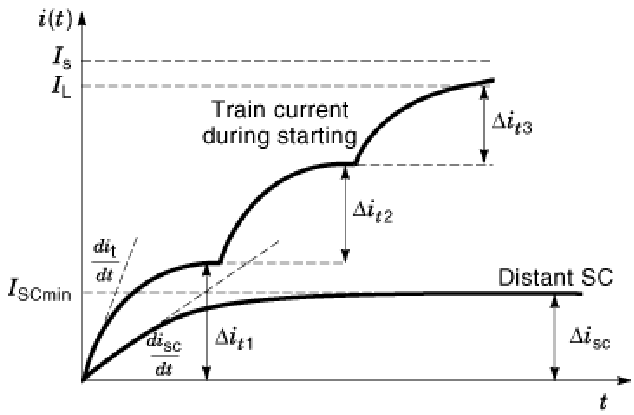

Fig. 9. Time curve of instantaneous current during distant short circuit and during starting of a train (with change of motor connections from series to parallel).

- Booster-transformer systems more efficient if provided with a return wire—Fig. 5(b), which allow one to reduce induction disturbance effects in telephone networks
- Ac systems with special three-phase–two-phase transformers (Scott, Leblanc, or Woodridge type) installed in the TS [Fig. 5(c)], to reduce asymmetry in the PUS
- Autotransformer systems [Fig. 5(d)], most expensive but most efficient, yielding lower voltage drops because the rail–catenary voltage $U/2$ is half the substation voltage U, so longer distances between TSs are possible and the system is suitable for *HSR*s or for heavy freight traffic (2×25 kV at 50 Hz).

A typical scheme for support of catenary and return-wire connections is shown in Fig. 20(c) below.

AC Low-Frequency Systems. The ETPSS of ac low-frequency systems is composed of high-voltage (*HV*) or medium-voltage (*MV*) lines connecting the PUS with TSs (Fig. 6) (equipped with static or electromechanical converters of three-phase industrial-frequency power to the one-phase $16\ \frac{2}{2}$. Hz or 25 Hz power required for Europe and the United States, respectively. In some ETPSSs, dedicated power stations or systems with one-phase low-frequency output are used.

Protection of AC Traction Supply Networks. Protective equipment for ac traction supply networks differs from that typically used in power utility systems due to the following peculiarities:

- EVs are moving along the railroad line, changing the load values and positions and thus the parameters and configuration of the circuit.
- There are big differences between short-term and long-term loads.
- Even if unilateral supply is applied in case of fault, the SC current may be energized by more than one feeder or even by a regenerating EV.
- Two-phase supply of the same section is prohibited.
- The load current may exceed the minimum value for a distant SC.
- Quick identification and elimination of the faulty section is required.

The TS is equipped with typical devices for transformers such as overcurrent, ground SC, Bucholtz, overtemperature, and differential protection, while the traction network requires the following protection equipment:

- Fast distance-directional impedance protection with current-step relay
- Thermal overload protection of the catenary and differential protection of the supply-cable
- Voltage protection against connecting different phases to the same section
- Lightning and overvoltage protection.

Moving Load on Power Supply Due to Electric Vehicles

The dynamic requirement for traction characteristic of an EV is to develop maximum available traction force F (torque M) during starting and then maintaining maximum power $P_{\max}$ within a range of speeds v up to maximum service speed.

Electric Vehicles with DC Motors. Dc series motors have characteristics very similar to those required, though with technical limitations on their traction characteristic [Fig. 10(a)] due to (1) adhesion and sliding, (2) rated power (heating), (3) commutation, and (4) the maximum speed $v_{\max}$. The maximum rated power of dc traction motors on locomotives is in the range 800 kW to 900 kW with weight/power ratios of 7 kg/kW to 12 kg/kW; for such motors in automobiles the corresponding ranges are 150 kW to 250 kW and 15 kg/kW to 20 kg/kW. Control of a dc series motor depends on its electrical and electromechanical characteristics:

$$\omega = \frac{U_{\mathrm{m}} - I_{\mathrm{r}}R_{\mathrm{s}} - I_{\mathrm{r}}R_{\mathrm{d}}}{C_{\mathrm{E}}\Phi k} \tag{2}$$

$$M_e = C_{\mathrm{M}} I_r \cdot \Phi \cdot k \tag{3}$$

$$\Phi = \frac{A I_{\mathrm{r}}}{B + I_{\mathrm{r}}} \tag{4}$$

where

ω = rotational speed
U_{M} = voltage supplying motor
I_{r} = motor rotor current
R_{d} = additional series resistance (starting resistance up to speed v_1)
R_{s} = motor's internal resistance
C_{E} = electrical constant
C_{M} = mechanical constant
ϕ = magnetic flux in motor
M_{e} = electromagnetic torque
k = coefficient of flux weakening
A, B = constants in approximation of magnetizing curve of a motor

According to Eqs. (2) 3, 4 it is possible to control the speed of the motor by:

- Controlling the supply voltage U_{M}
- Changing the additional resistance R_{d}
- Controlling the flux ϕ by means of its weakening (coefficient k)

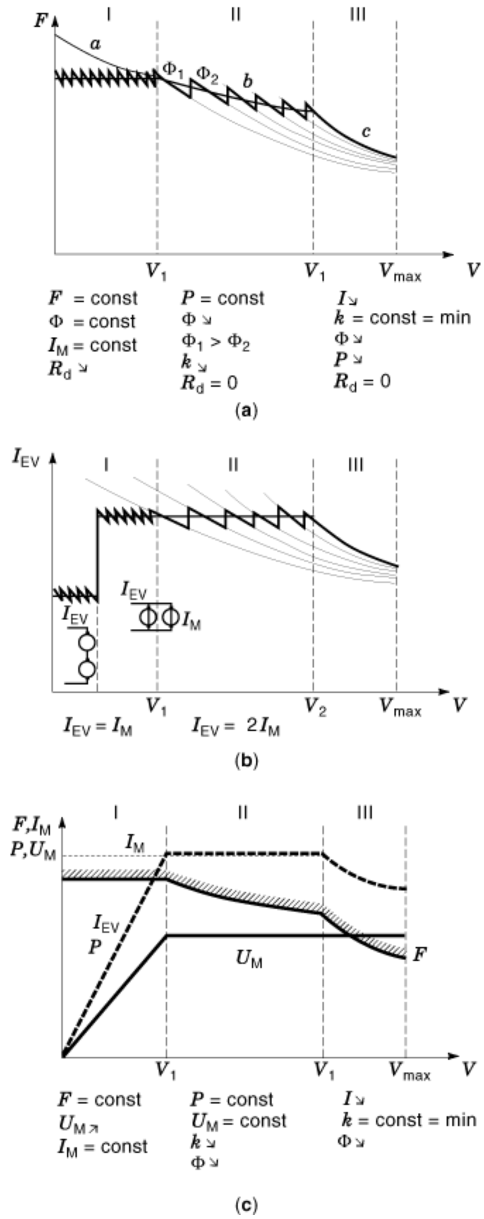

Fig. 10. Traction characteristics of EVs with dc motors: (a) rheostatic control and step-flux weakening, (b) switching the connection of motors from series to parallel during starting with rheostatic control and step-flux weakening, (c) chopper control during starting and flux weakening.

The traction characteristic of a dc-driven EV (traction fce F versus speed v) is divided into three zones [Fig. 10(b)]:

(1) Constant-torque mode for starting: maintaining I_r = const and Φk = const, so M_e = const, F = const, rheostatic control (variable $R_a\downarrow$) with change from series to parallel connection of motors [Fig. 10(b)], or voltage control [U_M, Fig. 10(c)] with a chopper or a controlled rectifier,

(2) Constant-power mode: P = const, I_r = const, U_M = const, $\Phi\ k \downarrow$ (k from maximum to minimum (magnetic flux weakening)

(3) Natural traction characteristic with reduced current I_r at speed $v > v_2$, $P \downarrow$, $\Phi\ k \downarrow$ (k = const = min), U_M = const = max. Rheostatic control of U_M is not efficient (dissipates energy) and creates traction characteristics like those shown in Fig. 10(b) for different values of R_d and levels flux weakening, whereas continuous control of U_M by static converters and continuous flux weakening $k \downarrow$ limits operation to the area below the curve of $F\ (v)$ in Fig. 10(c). The main disadvantages of dc commutator motors in an EV drive are high maintenance costs due to mechanical brush–commutator contact between stator and rotor, low reliability, and large weight and size per unit rated power.

Electric Vehicles with AC Motors. The development of power electronics and static power converters makes three-phase ac motors (induction or asynchronous) more convenient for use on EVs, due to lower maintenance requirements, lower size/power and weight/power ratios (up to 1.5 MW rated power per motor), and more convenient regenerative braking operation. Variable-voltage, variable-frequency three-phase control inverters allow one to obtain the required traction characteristic of EVs with ac motors.

The electromagnetic torque of an asynchronous motor is defined as

$$M_e = \frac{3}{\omega_s}\frac{p}{2}\frac{R_r}{s}\frac{U_s^2}{(R_s + R_r/s)^2 + [\omega_s(L_s + L_r)]^2} \qquad (5)$$

$$M_{e\max} = M_{cr} = \frac{3p}{4}\frac{U_s^2}{\omega_s^2(L_s + L_r)} \qquad (6)$$

where

$M_{emax}(M_{er})$ = maximum (breakdown) torque
U_s = supply voltage
p = number of poles
f_s = frequency of voltage U_s,
$\omega_s = 2\pi f_s$ synchronous speed
s = slip
$(\omega_s - \omega_r) = \omega_s$
ω_r = rotor speed

From Eq. (5) for $M_e\ (\omega_s)$ it is possible to formulate control algorithms (involving variation of the supply voltage U_s, frequency f_s, and slip s) for an asynchronous motor to get the required traction characteristic of the EV in the area limited by the curves for maximum torque, constant power, maximum slip, and maximum speed V_{max}. Similarly to the traction characteristic of a dc-driven EV, we may distinguish three zones of operation of an EV with an ac induction motor, within which the operation point may be chosen (Fig. 11):

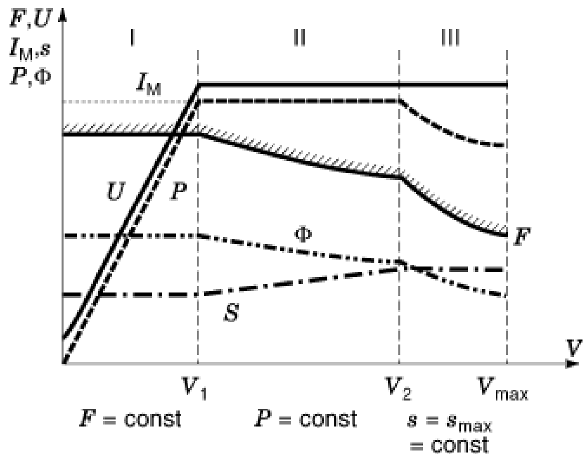

Fig. 11. Traction characteristics of EVs with induction motors and inverter control.

(1) Constant torque M_e (constant traction force F): M_e supply voltage U_s increases with speed v up to its nominal value U_{sn}, and f_s is increased to achieve U_s / F_s = const, slip s = const.
(2) Constant power: U_s = const; Φ ↓ stator frequency f_s increases above the nominal value f_{sn}: slip s increases up to the maximum value S_{max}; torque M_s is inversely proportional to speed ω_s
(3) Constant slips at its maximum value: U_s = const; power P_s motor current I_s and ϕ decrease; stator frequency f_s is still increasing proportionally to the speed; torque M and traction force F are inversely proportional to the square of the speed; zone is limited by the maximum speed V_{max}

The traction characteristic $F(v)$ of the EV, according to its dynamic motion requirements must develop a sufficient starting force and enough acceleration force to reach the maximum speed, taking into account the specifications for the traction drive (specified service speed, restrictions of speed on some sections, need to compensate deviations from the time table, changing grade, and curves).

An example of the traction force characteristic $F(v)$ and resistance to motion $W(v)$ for the same locomotive with dc motor drive but with different types of trains (curves W_1 to W_5) are presented in Fig. 12(a). The traction characteristic $F(v)$ of EVs with dc motors and step flux weakening makes a set of curves with a number of steady-state operating points (accelera- tion = 0) A_1, B_1, C_1 for train W_1, A_2, B_2, C_2, D_2 for train W_2. . . . For an inverter-supplied ac-motor-driven locomotive, the area of operation is limited only by these curves [Fig. 12(b)], so the possible steady-state operating points lie on the curves W_1 to W_5 below the limiting characteristic of the maximum $F(v)$.

Equation for an Electric Vehicle Motion. Power delivered to an EV is spent to produce the traction force F increasing the speed (acceleration) and overcoming the resistance W to motion of the train, which is given by

$$W = a_0 + a_1^v + a_2 v^2 + W_c \pm W_g \qquad [\text{N}] \qquad (7)$$

Here W is the total force of resistance to motion [N], v is the speed of the EV [km/h], and a_o, a_o, a_2 are approximate coefficients (dependent on the type of EV—usually obtained empirically) for the frictional and

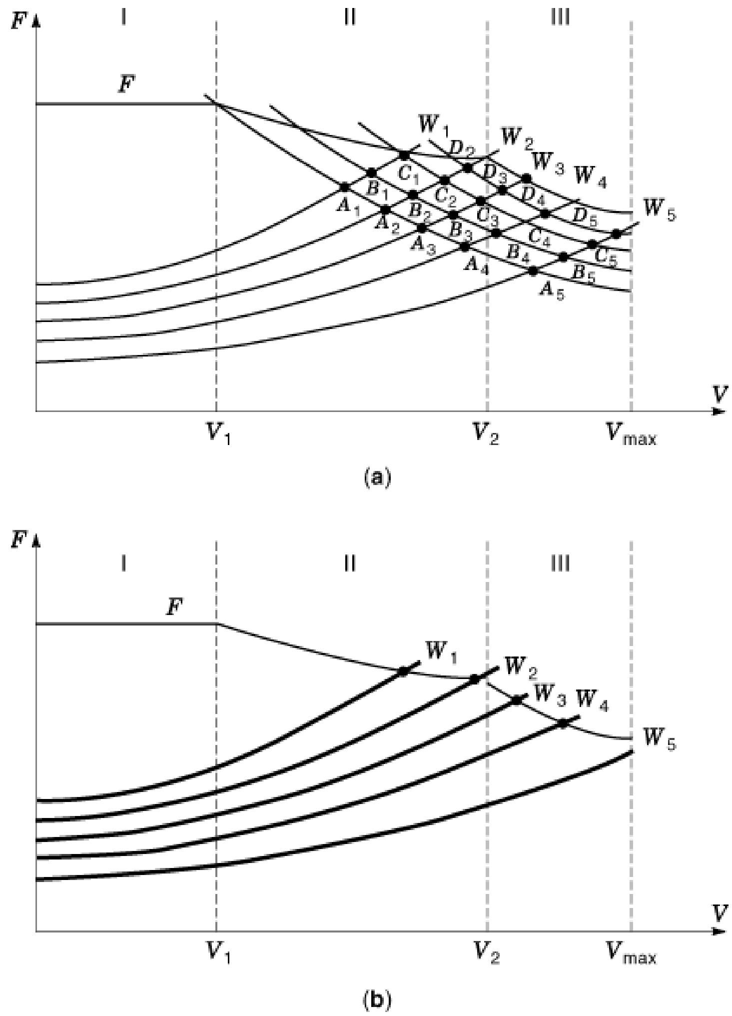

Fig. 12. Steady-state operation points (traction force F equal to resistance to motion) for different EVs and route profiles W_1 to W_5. (a) With dc motors and step flux weakening, the set of labeled points is accessible. (b) With ac motors and nonstep frequency control, all points within the area limited by the maximum available force F are accessible.

aerodynamic resistance. Typical dependences of these coefficients are as follows:

$$a_0 = K(m) + B(n)$$
$$a_1 = A(m)$$
$$a_2 = C + N$$

where

A, B, C = empirical constants,
K = coefficient dependent on the type of bearings
N = number of cars,

n = number of axles,
m = mass of the EV [tonnes,]

Also in Eq. (7), W_c is the local curve resistance [N] given approximately for 1435 mm gauge and classical trains by

$$W_c = mg\frac{700}{R-20} \qquad [N] \qquad (8)$$

where
R = radius of curvature of the track [m]
g = acceleration of gravity [m/s^2],

Modern vehicles with special self-steering wheel axles allow fitting to the rail at curves, which reduces curve resistance in comparison with a typical stiff wheel axle. Finally in Eq. (7), W_g is the local grade resistance (positive when the track upgrades and negative when it downgrades), given by $W_g = mgw$ [N]

$$W_g = mgw \qquad [N] \qquad (9)$$

where w is the grade of a section of track [‰]$_o$.]

$$w = h/s \qquad [m/km]$$

in which
h = equivalent height of grade [m]
s = length of the section with constant grade [km]

The force of resistance to motion may be expressed in thousandths (per mill, ‰ of the force of gravity on the EV. Usually for low-speed urban transport vehicles the average resistance to motion is assumed to be 4‰ 12‰ for trams and 12‰ 18‰ for trolleybuses. Additional resistance to motion that must be taken into account is caused by wind and by air resistance in tunnels. During coasting, resistance to motion is higher than during motoring (because the kinetic energy covers mechanical losses in motors and transmission). The increase in resistance to motion may be calculated using the increase coefficient k_c:

$$k_c = 1 + \frac{m_d}{m} \qquad (10)$$

where
m_4 = driven mass of the EV (the part of the total mass on driven wheels)

The kinetic energy E_k of a train at speed v is given by

$$E_k = k\frac{mv^2}{2} \qquad (11)$$

where
m = mass of train
k = coefficient that takes into account the energy of rotational parts

We have
1.03 for foreight wagons
1.05 for passenger coaches

k = 1.1–1.15 for multiple traction units

1.2 for streecars
1.3 for trolley buses

The equation of the EV dynamics (equation of motion) for rotational motion of the EV motors is

$$J\frac{d\omega}{dt} = M - M_{\mathrm{r}} \qquad (12)$$

and for the translational motion of the EV is

$$\frac{dv}{dt} = \frac{F - W}{mk} \quad \text{or} \quad v\frac{dv}{ds} = \frac{F - W}{mk} \qquad (13)$$

where
ω = angular velocity of a motor
J = moment of inertia of the train (with respect to an axle of a motor)
t = time
M = drive torque of a motor
M_{r} = resistance to motion torque at an axle of a motor
F = traction force
W = Total force of resistance to motion
s = distance

The useful mechanical power P_{m} delivered by the EV is equal

$$P_{\mathrm{m}} = Fv \qquad (14)$$

while the power P demanded from the source of energy is

$$P = \frac{1}{\eta} Fv \qquad (15)$$

where
η = efficiency of the source of power, supply network, main circuit of the EV with traction motors, and gear.

Unitary Energy Consumption. The specific energy consumption j is an average parameter given for a certaint type of EV of given mass, speed, route, and starting and stopping distances and is defined as the energy required to transport 1 tonne of mass a distance of 1 km:

$$j = \frac{A}{ms} \qquad [\mathrm{Wh/tonne \cdot km}] \qquad (16)$$

where
A = energy consumption [Wh]
m = mass [tonnes]
s = distance [km]

The unitary energy consumption depends significantly on the mode of operation of the EV—maximum and average speed, acceleration, and so on. Special optimization techniques are applied (including on board computer systems) to operate the EV with the minimum energy consumption for a given timetable. Note that quite apart from traction purposes, energy is required for auxiliary needs (air-conditioning, light, etc.) which increase the power demand by 10% to 20%.

In order to reduce energy consumption, *regenerative braking* of an EV can be used, whereby kinetic energy is transformed during braking (for stopping or on downgrades) to electrical energy (the EV operates as a generator), which may be

- Used onboard the EV or in the TS (after storage in batteries or elsewhere)
- Delivered via the power supply network to other EVs consuming current
- Returned to the TS through inverting rectifiers, which transfer energy to the ac power utility network

Electrical Parameters of the Traction Supply Network

The geometrical layout of wires and rails in the traction supply network (*TSN*) constitutes a complicated structure of mutually connected or coupled electrical components. These elements variously influence the electromagnetic and electromechanical processes occurring in traction systems (dc and ac). The main characteristic parameters of a TSN are R (resistance), L (inductance), M (mutual inductance), and C (capacitance); they are found by calculation or measurement and are usually expressed per kilometer of length. An equivalent simplified scheme of a catenary–rails–ground circuit is shown in Fig. 13(a). Usually during calculations of voltages and currents the capacitance C is neglected, but for transients, overvoltages, and resonances all parameters must be taken into account due to their significant influence on short-time phenomena in circuits. Some elements (rails, power rails, and messenger wires) are made of ferromagnetic materials, which causes their parameters to depend on current and frequency. The impedance of catenaries is dependent on their configuration and location with respect to ground, since the ground is a part of the return network, and may be described as

$$z = r_\mathrm{a} + j\omega L_\mathrm{i} + j\omega L_\mathrm{e} + j\omega M \qquad (17)$$

where

r_a = resistance per unit length [Ω/km]
L_i = internal inductance per unit length of the circuit [H/km]
L_e = external inductance per unit length of the circuit with ground return [H/km]
M = mutual inductance per unit length of the circuit [H/km]

which may be rewritten in the form

$$z = r_\mathrm{a} + j(x_\mathrm{i} + x_\mathrm{e} + x_M) \qquad (18)$$

where the x's are reactances per unit length. For nonferromagnetic magnetic materials the resistance r_a is equal to that for dc circuits. In case ferromagnetic materials are used in dc traction circuits during transients or with harmonics or in ac circuits, the *skin effect* must be considered, as the resistance increases for ac components:

$$r_\mathrm{a} = r_0 k \qquad (19)$$

where

k = coefficient dependent on frequency, cross-section, perimeter, and permeability (2–4)
r_0 = resistance per unit length for dc component [Ω/km],

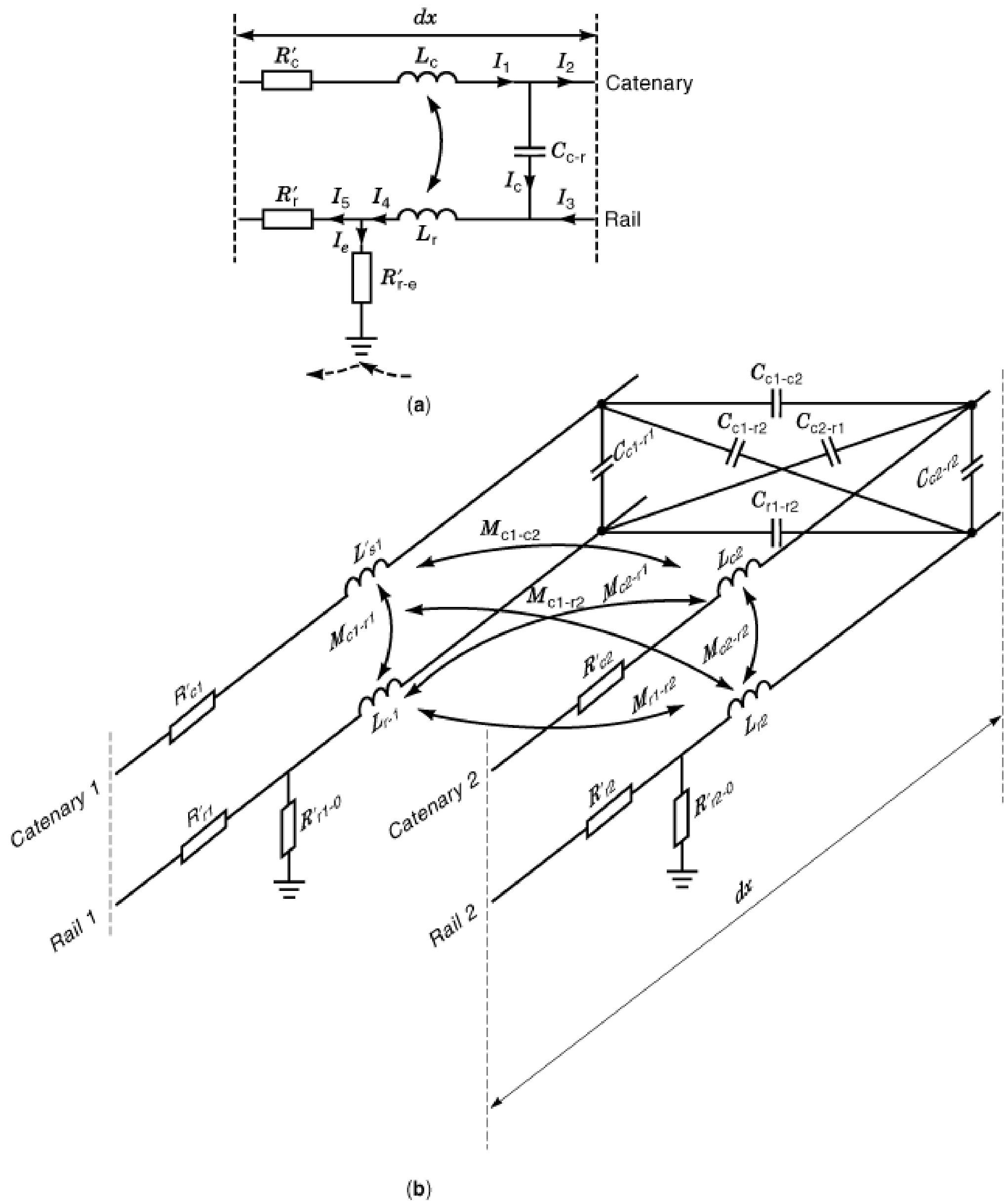

Fig. 13. A scheme of an elementary section of an electric traction power supply network with self- and mutual impedances: (a) simplified one-track, (b) dual-track.

The self-impedance z_r of a rail may be described by the following simplified equation (5):

$$z_{rl} = \frac{1}{R_c}\sqrt{\mu_r \mu_0 \omega \rho_r}(1 + j0.6) \qquad [\Omega/\text{km}] \qquad (20)$$

where

μ_o = 4 $\pi \times 10^{-7}$ H/m,

μ_r = relative permeability [for a ferromagnetic conductor with significant current change, see Table 6(a) (5)]

ρ_r = resistivity of a rail [Ω·m],

ω = $2\pi f$ with f = frequency [Hz]

R_e = radius of an equivalent circular cross section for a rail $=L/2\pi$ [m] where L = length of the perimeter of a cross section of a rail [m]

The internal impedance per unit length of a conductor 5 is

$$z_l = r_0 + j2 \times 10^{-4}\omega\frac{\mu_r}{4} \qquad [\Omega/\text{km}] \qquad (21)$$

where $\mu_r = 1$ for Al and Cu. The external impedance of a conductor (Carson–Clem–Pollaczek formulae) (5) is

$$z_e = \frac{\omega\mu_0 \times 10^3}{2\pi}\left(\frac{\pi}{4} + j\ln\frac{D_e}{R_c}\right) \qquad [\Omega/\text{km}] \qquad (22)$$

where D_e, the equivalent distance (depth) of the earth current from the surface of the ground, is given by

$$D_e = 659\sqrt{\frac{\rho}{f}} = 1.85\sqrt{\frac{\rho}{\omega\mu_0}} \qquad [\text{m}] \qquad (23)$$

and ρ is the ground resistivity [Ω·m]. The mutual impedance of conductors a and b (5) is equal to

$$z_m = \frac{\omega\mu_0 \times 10^3}{2\pi}\left(\frac{\pi}{4} + j\ln\frac{D_e}{D_{ab}}\right) \quad [\Omega/\text{km}] \qquad (24)$$

where D_{ah} is the distance between the conductors a and b [m]

For multiconductor networks there are formulas allowing one to make the calculations for the equivalent one-conductor circuit.

The equivalent impedance z_e of a messenger-wire-contact-wire circuit is equal to

$$z_c = \frac{z_w z_m - z_{wm}^2}{z_w + z_m - 2z_{wm}} \qquad [\Omega/\text{km}] \qquad (25)$$

where

Z_w = impedance of contact wire

Z_m = impedance of messenger wire

Z_{wm} = mutual impedance between contact wire and messenger wire

Table 6

(a) Changes of Relative Permeability μ_r of Steel Rails with 50 Hz Current (3)

Rms current (A)	μ_r
10	15
100	22
1,000	47
10,000	17

(b) Typical Electrical Parameters of a Traction Network[a] (2)

f (Hz)	*R* (Ω/km)	*L* (mH/km)	*C* (nF/km)
Dc	0.11	1.03	—
50	0.1101	1.044	20
1000	0.5386	0.846	20
2500	1.01	0.798	20

(c) Typical Measured Electrical Parameters of a Traction Network[b] (6)

f (Hz)	*R* (Ω/km)	*L* (mH/km)	*C* (nF/km)
Dc	0.08	1.4	—
140	0.13	1.35	23.4
1300	1.28	1.11	20.26
3400	3.61	1.1	17.5

[a] Hungarian State Railways. Double-track line. Overhead catenary: contact wire, 100 mm² Cu, and suspension wire, 50 mm² steel, connected in parallel. Signaling track circuits isolated on two rails (54 kg/m, R_{dc} = 0.0371 Ω/km. Ground resistivity 50 Ω · m.

[b] Polish State Railways. Single track. Catenary: 320 mm² Cu; rails: S49 with concrete ties.

For a pair of identical conductors connected in parallel ails of one track, rails or catenary of two tracks) the following equation is used:

$$z_{\mathrm{eq}} = 0.5(z_a + z_{ab}) \qquad [\Omega/\mathrm{km}] \qquad (26)$$

where

Z_{eq} = equivalent impedance of the pair of conductors
Z_{a} = self-impedance of the conductor,
Z_{ab} = mutual impedance between the two identical conductors a and b

When the rails are taken into account as a return network, the equivalent impedance z_1 of a catenary of one track is equal to

$$z_{\mathrm{I}} = (z_{\mathrm{c}} - z_{\mathrm{cr}}) + (z_{\mathrm{r}} + z_{\mathrm{rc}})\frac{I_{\mathrm{r}}}{I_{\mathrm{c}}} \qquad [\Omega/\mathrm{km}] \qquad (27)$$

where

Z_c = self-impedance of catenary [Ω/km]
Z_r = self-impedance of catenary [Ω/km]
Z_{er} = mutual impedance from catenary to rails [Ω/km]
Z_{rc} = mutual impedance from rails to catenary [Ω/km]
I_c = current flowing in catenary [A]
I_r = current flowing in rails [A]

For the equivalent circuit shown in Fig. 14(a) the voltage matrix equation is

$$\begin{bmatrix} \Delta U_c \\ \Delta U_r \end{bmatrix} = \begin{bmatrix} Z_c & -Z_{cr} \\ -Z_{rc} & Z_r \end{bmatrix} \begin{bmatrix} I_c \\ I_r \end{bmatrix} \tag{28}$$

with

$$\Delta U_c = I_c Z_c - I_r Z_{cr} \tag{29}$$

$$\Delta U_r = -I_c Z_{rc} + I_r Z_r \tag{30}$$

so the voltage drops between catenary and rails are

$$\Delta U = U_1 - U_2 \tag{31}$$

$$\Delta U = I_c Z_c - I\mathrm{r} Z_{cr} + I_r Z_r - I_c Z_{rc} \tag{32}$$

For directions of currents as in Fig. 14(b) (two-track railroad) the impedance matrix $\boldsymbol{Z}$ is equal to

$$\boldsymbol{Z} = \begin{bmatrix} Z_1 & -Z_{12} \\ -Z_{21} & Z_2 \end{bmatrix} \tag{33}$$

and for directions as in Fig. 14(c),

$$\boldsymbol{Z} = \begin{bmatrix} Z_1 & Z_{12} \\ Z_{21} & Z_2 \end{bmatrix} \tag{34}$$

After solving the equations when the currents are known in relation to the source (substation) voltage U, it is possible to calculate the lumped impedance of the circuit as the ratio of U to a sum of currents.

The representation of electric traction power supply circuits depends on the kind and purpose of the performed analysis, which may include:

- Balance of power and energy, with losses and energy consumption (parameters *R, L, C* for ac and *R* for dc systems)
- Voltage drops (*R, L* for ac and *R* for dc systems)

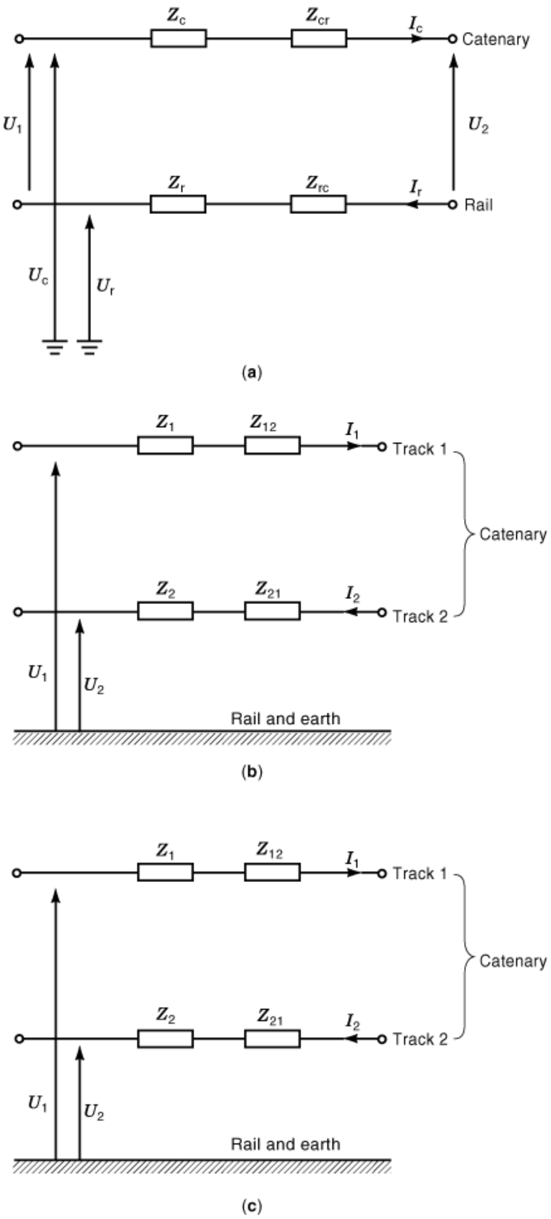

Fig. 14. An equivalent scheme for a traction power supply network with the ground as a return wire: (a) one-track, (b,c) dual-track.

- SC time-constant calculations (R, L of circuits for both ac and dc systems)
- Overvoltages and response to switching on and off (R, L, C for ac and dc systems)
- Frequency-dependent characteristics and high harmonics (R, L, C for ac and dc systems)
- Rail–ground voltage calculations; stray currents (R, L for ac and R for dc systems)

Typical parameters of a traction network are presented in Table 6(b) and 6 (6).

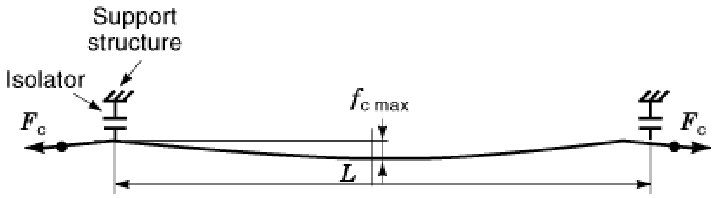

Fig. 15. Plain trolley wire: L, span distance; f_{cmax}, maximum sag; F_c, tensile force in the contact wire.

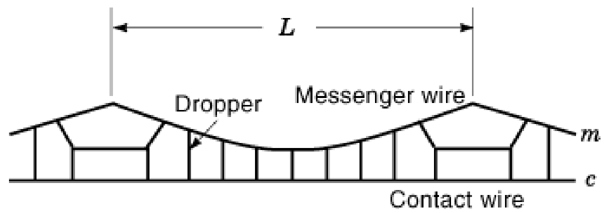

Fig. 16. Sagged simple overhead catenary.

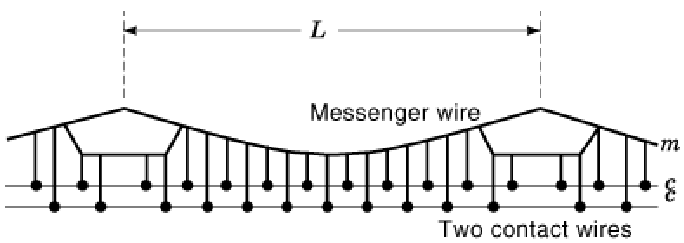

Fig. 17. Sagged multiple overhead catenary.

Overhead Catenaries

An overhead catenary (*OC*) consists of one or more wires elastically suspended above the EV, which receive current via a current collector (pantograph type or trolley type) installed on the roof. The design of an OC, which with the pantograph constitutes a vibrating system, depends basically on the requirement of maintaining proper contact with the pantograph at the required current and maximum speed. The main types of OC are as follow:

- Plain trolley wire (composed to contact wire only; used for low-speed EVsuch as a trolleybus or a streetcar) (Fig. 15)
- Sagged simple (Fig. 16) or multiple (Fig. 17) OC, composed of one or more messenger wires and suspended on one or more dropper contact wires
- Compound single or multiple OC (in Fig. 18 is shown a compound single OC with dampers to reduce mechanical oscillations)

Basic technical data of an OC are as follows (Fig. 19):

- System height h_k
- Height of contact wire suspension, h
- Span distance (between the adjacent support structures), L

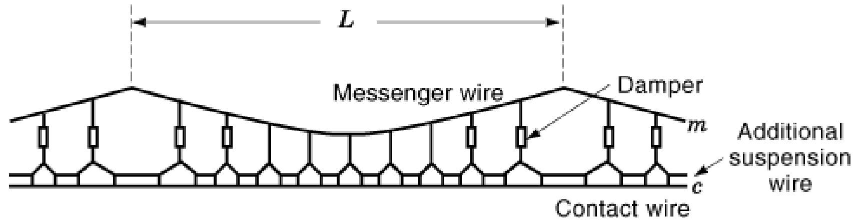

Fig. 18. Compound single overhead catenary with dampers.

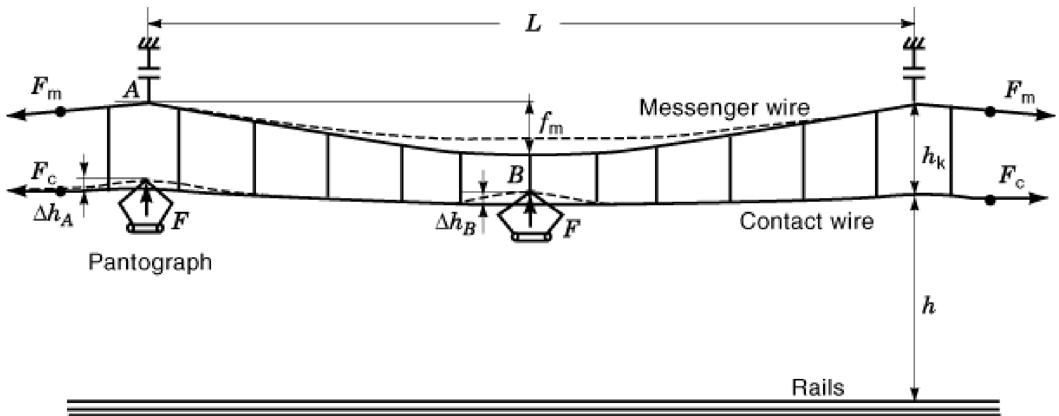

Fig. 19. Effect of a moving pantograph's position on an overhead catenary.

The suspension of an OC is made using special support structures (Fig. 20) with stagger (snaking) of the contact wire (Fig. 21), which allows use of the whole contact part of the pantograph pan and reduces local wear. Wear results from both mechanical and electrical effects. The contact force creates friction, which causes mechanical wear (larger force means more wear). Larger contact force, however, leads to lower equivalent contact resistance R_z and less electrical wear, which usually has major importance.

The heat Q emitted at the point of contact the pantograph pan with the contact wire is

$$Q = \int F\mu v\,dt + R_z \int [i(t)]^2\,dt \qquad (35)$$

where

F = contact force between pantograph and contact wire
μ = friction coefficient between pantograph and contact wire
i(t) = collected current
R_z = equivalent resistance between pantograph and contact wire

In order to maintain constant conditions of mechanical operation of an OC with a pantograph it is required to keep constant the forces tensioning the contact wire, F_c (Fig. 15), and the messenger wire, F_m (Fig. 19), which influence the sag f_c of the contact wire. The maximum sag can be calculated as follows (for the plain OC,

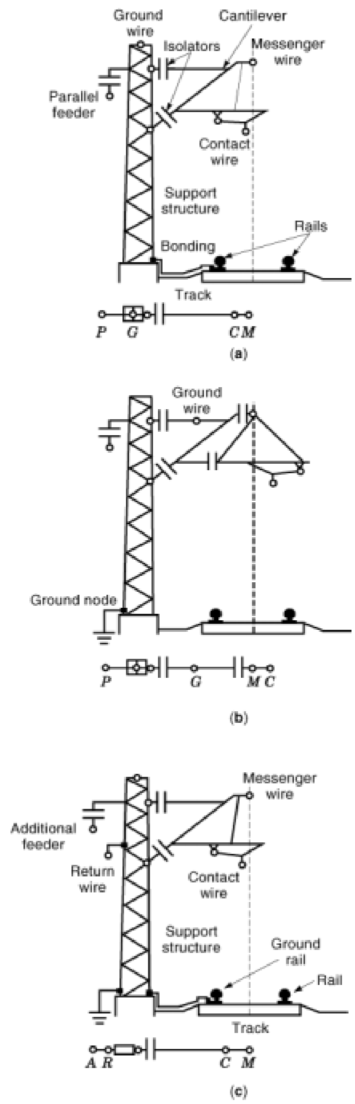

Fig. 20. Schemes of support structures of an overhead catenary and connections of wires: (a) with a parallel feeder and a ground wire connecting the supports, ground wire bonded to rail (dc system); (b) with parallel feeder and double isolation of catenary and ground wire connecting neutral parts between two isolators (dc system); (c) used in ac traction systems (bonding of a grounded support to the ground rail and return wire).

Fig. 15):

$$f_{\mathrm{c\,max}} = \frac{mgL^2}{8F_\mathrm{c}} \tag{36}$$

where

f_{emax} = maximum sag, midspan [m]

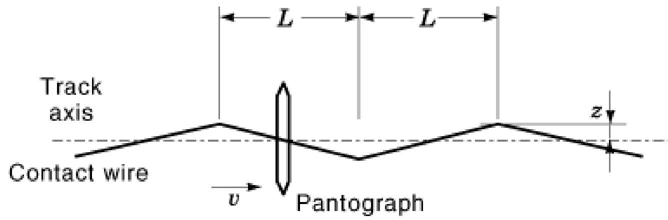

Fig. 21. Plan view of catenary, showing staggering of catenary and position of pantograph along the track axis.

m = mass of contact wire per unit length [kg/m]
L = span distance [m]
F_c = tensile force of contact wire [N]

The temperature-dependent length change ΔI of catenary between the two supports (span length) is given by

$$\Delta l = Lc_1 \Delta t \qquad (37)$$

where
Δt = temperature change [°C],
c_1 = coefficient thermal expansion of the contact wire lsqb;$°C^{-1}$].

To reduce this effect, mechanical tensioning equipment (TE) is used (a balance weight as in Fig. 22(b)–22(d), or a pneumatic or hydraulic system) on both ends of a section of catenary (up to 1600 m) including a number of spans. An typical simplified plan view of a span with two tensioning sections (1 and 2), with the indicated section of current collection frothe contact wires of both sections, is shown in Fig. 23. An OC that is first tensioned without the TE, is called a *noncompensated* OC (because the tensile forces change with the temperature); see Fig. 21(a). An OC with the messenger wire first tensioned without the TE and the contact wire tensioned with the use of the TE is called *half-compensated* [Fig. 21(b)]. If both the messenger wire and the contact wire are tensioned with the TE [Fig. 21(c,d)], the OC is called *fully compensated*.

The *contact wire* is usually made from Cu, possibly alloyed with Ag or Si; typical cross sections are 100 mm^2 to 170 mm^2. A *messenger wire* is typically made of Cu, bronze, steel, or combined steel and aluminium, with cross section 50 mm^2 to 180 mm^2. *Parallel feeders*, usually suspended on the other side of the support structures (Fig. 20) to increase the equivalent cross section of the catenary, are made of Cu or Al (with Al–Fe wire), as are the protective *ground wires* used for connecting bonded [Fig. 20(a)] or grounded [Fig. 20(b)] support structures. Typical parameters of overhead catenaries are given in Table 7. Conductor rails in third-rail [Fig. 2(b)] or fourth-rail systems are made of steel, aluminum (low wear resistance), or aluminum with a steel surface (good conductivity and wear resistance). There are different types of current collectors (*CC*s) used: trolley collector [Fig. 2(a)], shoe-type [Fig. 2(b)], bow collector, and pantograph (Fig. 19). The pantograph's pan head is made of Cu, graphite, or metal-plated carbon with addition of lubricant. During running of the EV its pantograph, pushed by a force F, raises the contact wire (CW) to a height Δh that depends on F, the CW's elasticity, the speed of the vehicle, the vibration of the vehicle, and the pantograph's mass. (In Fig. 19 two positions of the pantograph are shown: at the point A close to the support, and at B, the midspan of the OC, with heights denoted respectively as Δh_A and Δh_B) The total force F is the sum of the following forces:

$$F = F_s \pm F_\mu \pm F_i + F_a \qquad (38)$$

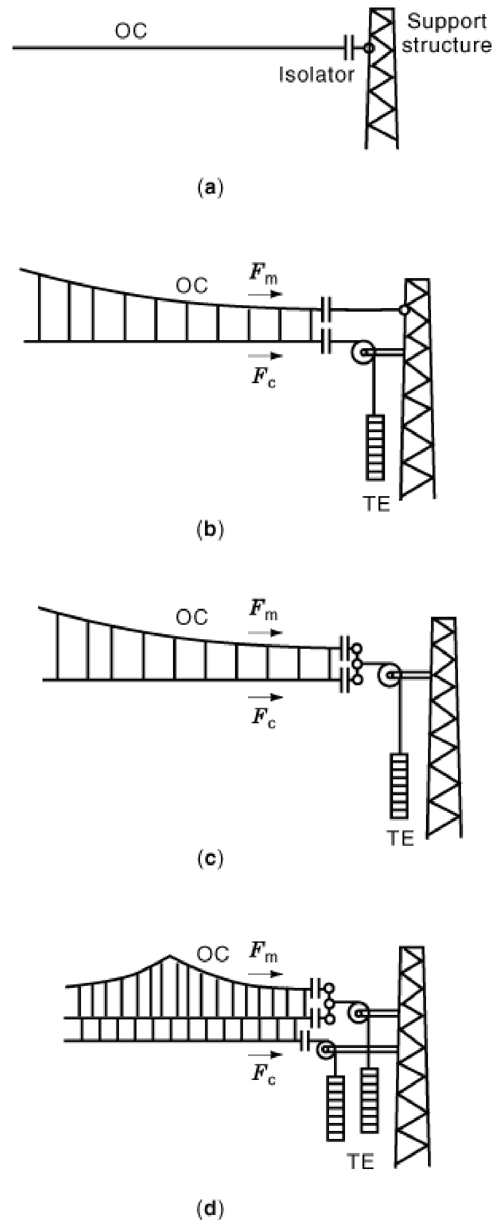

Fig. 22. Types of overhead catenary with compensation equipment: (a) noncompensated, (b) half-compensated, (c, d) fully compensated.

where

F_μ = friction in the pantograph joints, (− for movement up; + for down)
F_{i} = inertia force (− for movement up; + for down)
F_{a} = aerodynamic interaction (vertical component of aerodynamic force)

By sinusoidal approximation of the contact point (pantograph–contact-wire trajectory) or its first harmonic (Fig. 24) it is possible to describe its vertical movement (ordinate y) along the span (position x) with the

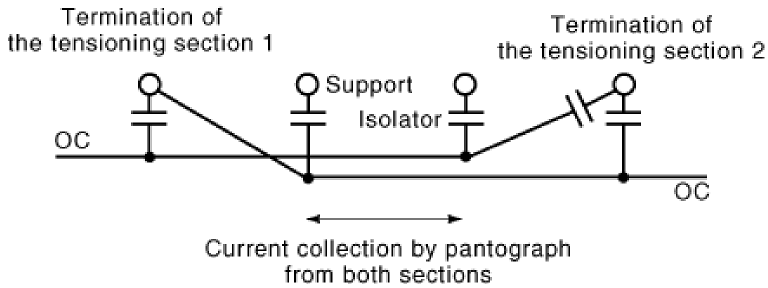

Fig. 23. Plan view of two tensioning sections of an OC.

Table 7. Typical Data on Overhead Catenaries for High-Speed Railroad Lines[a]

Element	Cross Section (mm^2)	Tensile Force (N)
	1.5 kV dc system[b]	
Contact wire	2 × 150 Cu	F_c = 17,500
Messenger wire (main)	116 bronze	F_{m1} = 23,000
Messenger wire (additional)	143 Cu	F_{m2} = 8100
	3 kV dc system[c]	
Contact wire	2 × 150 Cu	F_c = 2 × 15,000
Messenger wire (main)	120 Cu	F_{m1} = 13,750
Additional wire	190 Cu	
	15 kV ac, $16\frac{2}{3}$ Hz system[d]	
Contact wire	100 Cu	F_c = 15,000
Messenger wire	70 Cu	F_m = 15,000
	25 kV ac system[d]	
Contact wire	150 Cu	F_c = 20,000
Messenger wire	65 Cu	F_m= 14,000

[a] Span length 55 m to 73 m.
[b] Pantograph static force 80 N to 90 N.
[c] Pantograph static force 80 N to 120 N.
[d] Pantograph static force 55 N to 70 N.

following assumptions: infinite catenary length, constant span length L, constant speed v of the EV, and constant parameters of catenary and pantograph. We have

$$F_i = -m_0\,\omega_0^2\,H\sin\omega t \tag{39}$$

$$F_a = k_i v^2 \tag{40}$$

$$\omega_0 = \frac{2\pi v}{L} \tag{41}$$

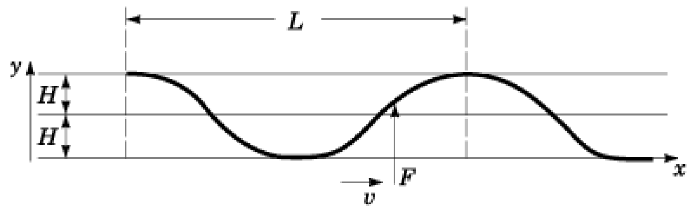

Fig. 24. Trajectory of vertical position y the contact point between pantograph and contact wire along the span x.

where

ω_0 = natural frequency of pantograph
m_0 = equivalent mass of pantograph referred to the contact point
k_i = coefficient of vertical aerodynamic force on pantograph

Then the simplified equation of the contact point x is

$$[m_0 + m_\mathrm{s}(x)]\frac{dy^2}{dt^2} + r_\mathrm{s}\frac{dy}{dt} + \frac{y}{e(x)} = F_\mathrm{s} \pm F_\mu + F_\mathrm{a} \qquad (42)$$

where

$m_\mathrm{s}(x)$ = equivalent mass of catenary (referred to the contact point)
y = $y(t)$= ordinate of contact-point trajectory
r_s = coefficient of friction
$e(x)$ = elasticity of catenary

In practice the characteristics of the catenary are assessed by calculation and measurement, from which the following parameters are obtained:

- The frequency of free vibrations, ω_s, which may be approximated by

$$\omega_\mathrm{s} \approx \frac{0.5}{L}\,2\pi\sqrt{\frac{F_\mathrm{m} + F_\mathrm{c}}{m_\mathrm{m} + m_\mathrm{c}}} \qquad [\mathrm{m/s}] \qquad (43)$$

where

F_m = tensile force of messenger wire [N]
F = tensile force of contact wire [N]
m_c = mass per unit length of contact wire [kg/m],
m_m = mass per unit length of messenger wire [kg/m]
L_e = span distance [m]

In case the pantograph is moving at the critical speed v_er equal to

$$v_\mathrm{cr} = L\omega_\mathrm{s} \qquad (44)$$

mechanical resonance occurs and $\omega_\mathrm{s} = \omega_\mathrm{o}$.

The coefficient of nonuniformity of static elasticity,

$$\Delta e_{\%} = \frac{e_{\max} - e_{\min}}{e_{\max} + e_{\min}} \times 100 \qquad [\%] \tag{45}$$

where

$e_{\max}$ = midspan elasticity
$e_{\min}$ = elasticity at support structure

The propagation velocity v_{w} of the transverse waves,

$$v_{\mathrm{w}} = \sqrt{\frac{F_{\mathrm{m}} + F_{\mathrm{c}}}{m_{\mathrm{m}} + m_{\mathrm{c}}}} \tag{46}$$

The reflection coefficient for transverse waves,

$$r = \frac{\sqrt{F_{\mathrm{m}} \cdot m_{\mathrm{m}}}}{\sqrt{F_{\mathrm{m}} \cdot m_{\mathrm{m}}} + \sqrt{F_{\mathrm{c}} \cdot m_{\mathrm{c}}}} \tag{47}$$

Doppler's coefficient

$$\alpha = \frac{V_w - v}{V_w + v} \tag{48}$$

where v is the speed of the EV.

The amplification coefficient

$$\gamma = \frac{r}{\alpha} \tag{49}$$

The coefficient of contact continuity,

$$k_{\mathrm{s}} = \frac{\sum t_0}{t_p} \times 100 \qquad [\%] \tag{50}$$

where

t_{o} = time that wire and pantograph are out of electrical contact
t_{p} = time of EV run on the catenary section

For high-speed railroad lines with speeds of 200 km/h to 250 km/h, the catenary parameters are given in Table 8.

Systems Approach to Electrified Ground Transportation

In order to represent the technical complexity of electrified ground transportation (*EGT*) treated as a multivariable system, the rail system may be divided into a finite number of subsystems (Fig. 25), where

Table 8. Catenary Parameters for High-Speed Railroad Lines (200 km/h to 250 km/h)

$F_s = 0.7–1.1$ Hz
$V_{cr} > 250$ km/h
$\Delta e < 10–20\%$
$V_{max} < 0.9 v_w$
$R \leq 0.45$
$\alpha > 0.15$
$k_s < 1.5\%$
$3.5 > \gamma > 1.0$

power utility system
traction substation (ac or dc)
= traction power supply system
= electric vehicles
= traction signaling, command, and control system
= railroad
= demand for transport service (freight and passenger)
= influence of EGT system (EGTS) on the environment and surrounding technical infrastructure
= performed transport service (in passenger-kilometers, passengers per hour, or tonne-kilometers of freight)

The systems approach allows us to define internal and external interdependences between subsystems, which are described as follows:

U_1 = system voltage; power capacity of PUS (external input)
Y_1 = voltage; short-circuit power of PUS at point of connection of TS to PUS
Z_1 = influence of traction substation load on PUS (changes of load, harmonics, asymmetry)
U_2 = voltage; short-circuit power of PUS at inlet busbars of TS
Y_2 = currents of feeders; voltage at output busbars of TS
U_3 = voltage at output busbars of TS; currents taken by trains
Y_3 = voltage at pantographs of EVs; currents in the contact line
Z_3 = locations of EVs in violation of the timetable
Z_4 = voltage in the contact line below the specified limit, causing abnormal operation of TPSS
U_4 = trains' positions and speeds as required by timetable; data and commands from control and signaling system delivered to trains; voltage in the contact line
Y_4 = actual mode of operation of trains; power; current; actual location of trains
Z_5 = actual traffic situation on the line: traffic disturbances, delays, compatibility disturbances (harmonic distortion caused by power traction circuits in CS installations)
Y_5 = trains' positions and speeds as required by timetable; data and commands from control and signaling system delivered to trains
U_5 = traffic technology; specified timetable (type of trains, masses, speeds, etc.) according to expected and real transport service demand
U_6 = return current of EVs; mechanical load on track due to EV movement

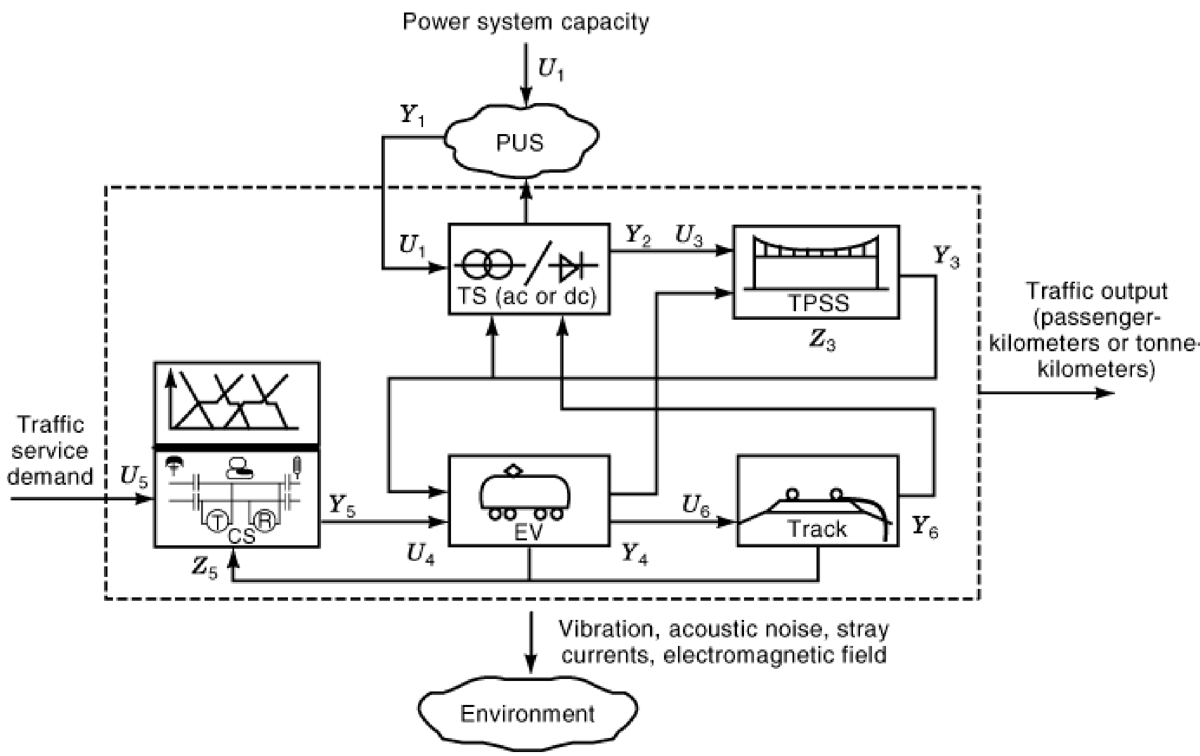

Fig. 25. Electrified ground transport system divided into a number of subsystems.

Y_6 = current distribution in rails; stray currents; rail–ground voltage

Choice of Electric Traction System

The choice of the electric traction system depends on many different conditions, such as:

- Type of the transport system (urban, suburban, long distance)
- Traffic capacity and expected power demand
- Environmental impact and safety
- Availability of technical infrastructure (e.g., public power supply system and its power capacity)
- Compatibility with existing transport systems
- Cost–benefit analysis of different options

The choice of the system voltage determines the required parameters of the power supply structure, the rolling stock, and the surrounding technical infrastructure.

Sizing of Power Supply Equipment and Installation

Calculation of the required power to be delivered to an EV is based on the assumed traffic volume and the resulting timetable. From *traction calculations*—solving the equations in Eq. (13) of EV motion—the power demand of vehicles for peak traffic hours (maximum power demand) is obtained and used for sizing the power equipment. Then the power flow in the supply system (dc or ac) and the loads on the catenary, feeders, and traction substation are determined. The following parameters are calculated to evaluate the required parameters of the installations:

- Values of rms current (average over 15 min for catenary; over 30 min and 1 h for feeders),
- Peak values of feeder currents (to set the level of short-circuit protection),
- Power demand from traction substation and its time profile
- Minimum allowed voltage at pantograph of EV and on busbars of traction substation
- Voltage drops in rails (leading to safety hazards and stray currents)
- Power delivery efficiency

The calculated values must be (within a certain margin) below the capacity of the power supply installations, and the power required from locomotives must be within their capacity. As the above usually requires simultaneous solution of a number of electromechanical equations of EV motion and electrical equations of power flow, modeling and simulation methods are widely used.

A simplified method of sizing is based on knowledge of j, the specific energy consumption of an EV, from which an average power demand per unit length, P, on a section of the power supply is obtained:

$$P = lnjm/v \qquad \text{[Wh/km]} \qquad (51)$$

where

n = frequency of traffic [trains/h]
j = specific energy consumption [Wh/tonne·km]
v = average speed of EV [km/h]
m = mass of a train [tonne]
l = length of a power supply section [km]

Assuming an average voltage in the contact line, the current load per unit length of a section may be calculated, and thence the load on the traction substation (using dc or ac power flow calculations). Sizing of ac power supply installations from a public utility network is based on the obtained TS load profile.

Modeling and Simulation Methods as a Tool for Analysis of an Electrified Ground Transport System

Modeling and simulation of such a complex system as an E*GTS* involve many interacting problems concerning subsystems (Fig. 25). Many assumptions and simplifications must be made in formulating the model and calculations. The preparation of an EGTS simulator requires not only analytical, but also logical techniques to obtain either a theoretical or a methodological solution. The process of modeling and simulation consists of:

- Splitting the EGTS into functional subsystems (Fig. 25)
- Constructing a mathematical model of the each subsystem with sufficient accuracy

- Reviewing the algorithms and other tools that might be applied to these models, taking into consideration the available computing facilities
- Solving the identified problems using suitable mathematical methods and iterative procedures

In view of the complexity of EGTSs, models in practice are oriented towards the following main aspects:

- Electromechanical problems (motion of EV, power demand of EV, influence of voltage conditions on traction characteristics of EV). Main model: equation of EV motion.
- Power flow problems (power flow analysis in traction system and PUS, sizing of equipment and installations). Main model: power flow model of traction system (dc or ac) and PUS.
- Electromagnetic problems concerned with harmonics and transients: disturbances, SCs, dynamic states of the system. Specialized circuit and electromagnetic-field-oriented models are required to analyze short-term interdependences between subsystems and elements.
- Traffic technology (timetable, traffic flow, management).

Simulation methods are applied for the preliminary study, design work, and verification of the real system's operation, as some experiments are difficult or even impossible to carry out on a functioning transport network (7,8,9,10,11,12,13,14,15,15).

Control and Signaling in Transportation Systems

A transportation system has to ensure appropriate (as high as economically possible) reliability, availability, maintainability, and safety (*RAMS*). All RAMS figures are increasing with the introduction of new systems and new technologies, although they never reach 100%. New systems also allow increased speed and line capacity and decreased traveling times for high-speed and heavy-traffic lines, as well as improved economy of operation, especially for secondary and low- traffic lines.

Conventional Signaling Systems (with Colored Light Signals). Widely used conventional signaling systems (with colored light signals) are based on track occupancy checking devices. The track is divided into sections. Occupancy of a section of track may be checked by track circuits or by axle counters. Some railroads have also tried special infrared train-end devices, but they are not used in practice because of operational problems. On the basis of the track occupancy information, special installations—block systems on lines and interlocks at stations—prepare routes for trains. A route for a train must be set using only unoccupied tracks. Then the route has to be proven and locked. When the route is locked for a train, a color is displayed on the light signal that gives permission to the driver to enter the route. The colors displayed on the signal depend on the railroad administration and the traffic situation.

There are two basic principles for signaling: speed signaling (signal shows maximum allowed speed for passing it and the next signal) and distance signaling (signal shows distance to the point that should not be passed—usually as a number of unoccupied block sections after the signal for which the route is set, proven, and locked). As a result, information is passed to the driver, who is responsible for keeping the train running within the limits.

Track Circuits. The basic method of track occupancy detection is the separation of the track into *blocks* equipped with track circuits. Widely used track circuits are *low-frequency track circuits* with insulation joints and *jointless track circuits*. They are described below. Other means of detection of trains on tracks include impulse track circuits (used on nonelectrified railroads), binary-coded track circuits, and axle counters.

Low-Frequency Track Circuits. These are used mainly on dc electrified systems. Both rails are used to transmit an ac signal from a low-voltage transmitter T1 to a receiver R1 (where T1 is situated at one end of the circuit and R1 at the other) or receivers R3A and R3B (where T3 is situated at the center, and R3A and

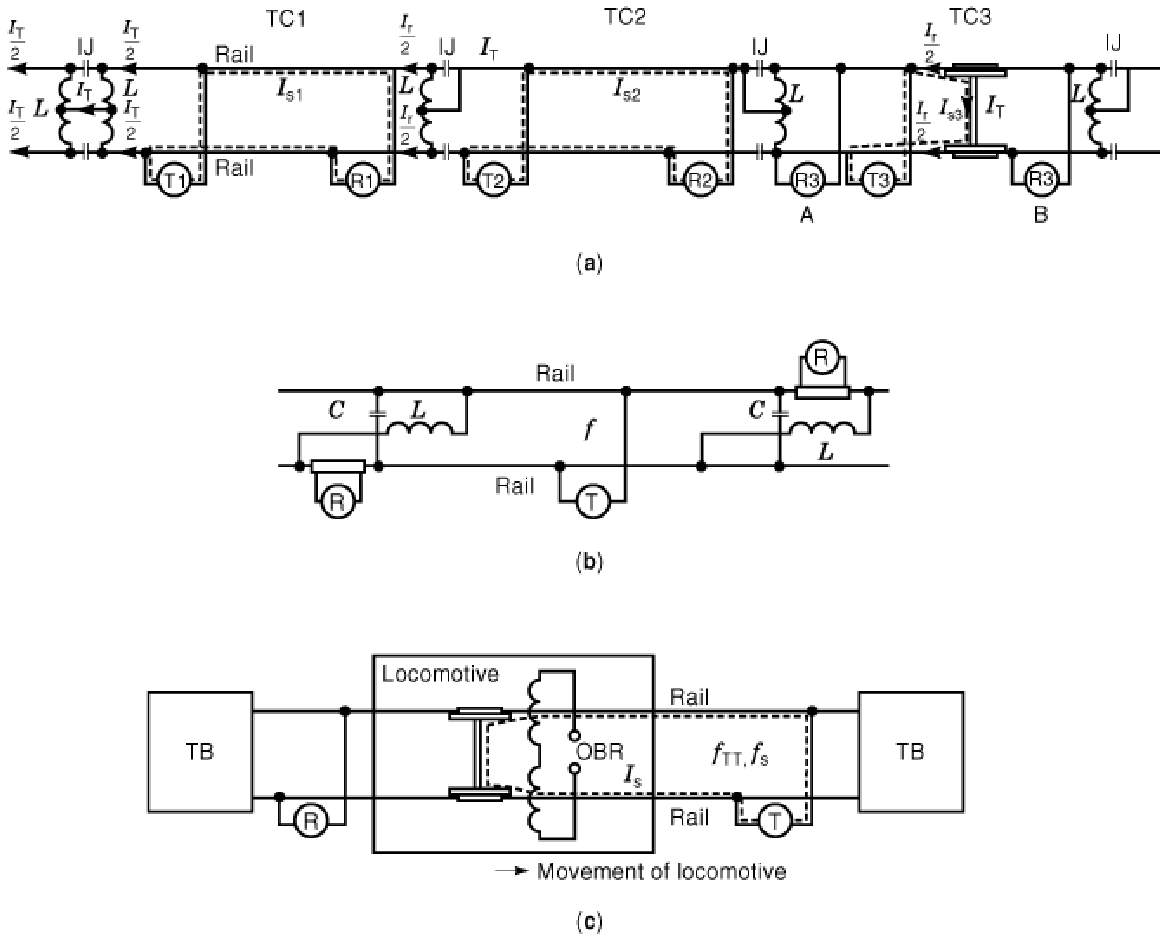

Fig. 26. Track circuits: (a) low-frequency track circuits with insulated joints (*IJ*), both single-rail (TC2) and double-rail (TC1, TC3); (b) jointless track circuit; (c) track-to-train communication using jointless track circuit.

R3B at the ends) [Fig. 26(a)]. Block rails are separated by insulation joints (*IJ*) at both ends of the block. As rails are used for the return path of the traction current I_T (both rails in double-rail, TC1, but one rail only in single-rail, TC2), inductive bonds L are used, which present high impedance at the signaling frequency, but low resistance to the dc current I_T. When there is no train on the block (TC1), relay R1 is energized with signaling current I_{s1} from T1. In case a train occupies the track (TC3), the signaling current I_{s3} is shunted by a wheel set of the train and relays R3A and R3B are deenergized, signaling the occupancy of the track, which is shown by changing the color of a semaphore light. Typical operating frequencies are: 25 Hz, $33\frac{1}{3}$ Hz, 50 Hz, 60 Hz, 75 Hz, $83\frac{1}{3}$ Hz, 100 Hz and 125 Hz. The length of the circuit depends on the frequency, voltage, and power of the transmitter and on the electrical parameters of the rails, ties, and ballast. The track circuit is described using transmission-line equations. Single-rail dc track circuits used on ac electrified railway lines are based on the same principle.

Jointless Track Circuits. Here two rails are used both for the traction return current and for the signaling current, whose frequency f is in e audio range (typically 1.5 kHz to 3 kHz) [Fig. 26(b)]. The signaling current is generated by a transmitter T and received by a tuned receiver R. No insulated joints are used, and the track circuit is electrically terminated at its ends by terminating bonds (*TB*s) composed of L and C elements. A TB presents low impedance at the signaling current frequency f, but high impedance at other signal frequencies. In order to avoid interference, neighboring track circuits operate at different frequencies. Other means of detection of a train on the block include (1) comparison of the phase and amplitude of signals detected by receivers at both ends of the circuit from a transmitter at the center, and (2) frequency modulation.

Vigilance; Automatic Train Protection, Control, and Operation. As long as track-to-train communication takes place via the driver's eyes, onboard systems are not able to monitor driver behavior. The only possibility is a passive vigilance device periodically (every n seconds) checking only the presence of the driver (e.g., the *dead man* used by British Railways). Track-to-train transmission must be available to introduce active vigilance devices. As an example we mention SHP, used by Polish State Railways, which checks driver vigilance 600 m before each signal. If the driver does not operate the vigilance button within 5 s, an emergency brake is applied.

An *automatic train protection* (*ATP*) system is an intelligent overlay on the conventional signaling system. The track–train transmission includes the maximum speed and (possibly) the permitted distance. The onboard ATP equipment does not allow the driver to override the limits. As examples we mention many systems used by European railways: ZUB, EBICAB, KHP, INDUSI, ASEC, SELCAB, BACC, EVM, KVB, and others.

An *automatic train control* (*ATC*) system combines ATP functions with some functions of conventional signaling systems. Examples are LZB and TVM. In practice the boundary between ATP and ATC systems is not strictly defined, so we speak of ATP–ATC systems.

ATP–ATC systems may be based on spot transmission, on transmission, sections, or on continuous transmission. Spot transmission means sending data at certain points where the train passes a trackside device: a transponder (balise), short track circuit, or cable loop. Sent information is then valid at the moment of transmission. If an in-fill section (leaky cable, medium loop, or local radio) is added before the spot device, a stop signal that has changed to a proceed signal can be seen by the system without the need to stop. Continuous transmission (via long loops, coded track circuit, or radio) meets the requirement that the information be up to date.

As an example we consider jointless track circuits, which are used for both track-occupancy detection and track-to-train communication [Fig. 26(c)]. The terminating impedae bonds (TB) are to be tuned both to the track signal frequency f_s and to the track-to-train signal frequency f_{TT}. The signal I_s flowing in the rails is detected by an onboard receiver (OBR) mounted ahead of the first axle under the locomotive moving from the receiver R to the transmitter T (the track current I_s is shunted by the axles and does not flow in the rails behind the first axle).

An *automatic train operation* (*ATO*) system is an autodriver (like an autopilot in an airplane). Such a system requires more information, as for example the start and length of the platform and the side on which the platform is situated. It may take into account timetable information and energy-saving criteria. Such systems are used in subway trains, where there is no mixed traffic (programming of ATO is much more complex for mixed traffic such as occurs on ordinary railroad lines) and working conditions for drivers are bad (running mostly underground).

European Train Control System—A New Unified Automatic Train Protection and Control System. The European railroads, together with the European signaling industries, are preparing a new standard for track–train transmission and supervision of drivers. It is the European Train Control System (*ETCS*), functionally similar to the Advanced Train Control System (*ATCS*) specified by the Association of American Railroads. *ETCS* is designed for passenger and freight traffic command and control in order to achieve interoperability of trains between different railroad networks in Europe (no need to change locomotives or drivers, or even to stop trains at borders). Data received from the track, together with data available onboard, are used for calculation of static and dynamic speed profiles, which are continuously compared with actual train speed and traveled distance. Most of the functions can be performed by either the trackside or the onboard equipment.

ETCS guarantees safe operation of trains on the set route and within the speed limits, especially on high-speed lines.

ETCS is divided into the following three levels of application:

- *Level 1.* Train is equipped with onboard safety computer, maintenance computer with man–machine interface, recorder, odometer, and antenna to receive data from track installations. Track is equipped with switchable beacons connected via *line-side electronic units* (*LEU*s) to the signals or directly to the interlocking or blocking system. Optionally level 1 may be equipped with in-fill channels for actualization of data received from trackside. This may be done by Euro-loops, or by a *specific transmission module* (*STM*).
- *Level 2.* Train is additionally equipped with the *ETCS* EIRENE radio. Track is equipped with nonswitchable beacons (used for location reference and for transmission of permanent data) and a *radio block center* (*RBC*), which communicates on one side with interlocks and blocking systems and on the other side with trains, giving all switchable information. Colored light signals are no longer required (if all entering trains are equipped with *ETCS* level 2 onboard equipment), as their function is taken over by radio transmission.
- *Level 3.* Train is additionally equipped with a *train integrity unit*, which forms a basis for the supervision of track occupancy. Track circuits and axle counters are no longer required. Level 3 allows trains to operate under moving-block schemes (which increases the line capacity), where the headway between trains is continuously regulated using information about the position and the speed of the preceding train.

Traffic Management Systems. On top of the control and signaling systems there is a dispatching system whose aim is traffic management. Different railroads use different dispatching systems. Introduction of a unified ATP–ATC system—*ETCS*—will allow unification of traffic management. The European railroads are planning a new standard for traffic management: the European Railway Traffic Management System (*ERTMS*). They have already started to define its scope. It includes at least the *ETCS* control command, and traffic management functions. It may also include management of locomotives and cars, power supply management, ATO, timetable planning, track maintenance planning, and other functions.

Impact of an Electrified Ground Transport System on the Environment and the Technical Infrastructure

One of the main advantages of electrified over nonelectrified transport is its lower impact on the environment. Namely, an EGTS makes less noise; it uses electric energy, which may be produced far away from the area of its consumption, so there is no emission of fumes along the line; and its transport capacity and energy efficiency are larger, so that it is more reliable and cost-effective. However, an EGTS has some disadvantages: the large capital investment required, landscape problems due to overhead catenares and the use of land for TSs and power lines, and technical problems such as the effect of TSs on the power utility system, electromagnetic compatibility, and stray currents.

Impact of Traction Substations on Power Utility Systems

The effect of traction substations on the public power utility system (*PUS*) supplying them depends on the type of electric traction system: dc or ac. Dc traction substations present a load that is nonlinear (current harmonics are created by rectifier or inverter operation) and nonsteady (*flickers* are created by changes of power demand). Ac (50 Hz) traction substations—apart from harmonics (generated by power electronic converters installed in electric vehicles), *reactive power loads*, and fluctuations of taken power—create non-three-phase loads, which cause *asymmetry* in the PUS.

Harmonic Distortion in a Public Utility System. International and country standards impose limits on the individual or total harmonic distortion (*THD*) harmonics caused by nonlinear loads and converters on a PUS. These limits depend on the voltage, and use of a high-voltage supply with high power capacity and fault level significantly decreases the distortions. When it is impossible to decrease harmonic distortion below the limits, the traction substation should be equipped with filters or be supplied individually via a separate line or transformer.

Asymmetry. Ac single-phase traction substations cause unbalance in three-phase PUSs, which then causes *negative phase sequence* current (nps). The level of nps can be assessed for one unbalanced load as follows (15):

$$\text{nps} = \frac{S_\text{T}}{S_\text{sc3}} \times 100\% \qquad (52)$$

where

S_T = traction line-to-line load

S_sc3 = three-phase short-circuit level at point of TS connection to PUS

For ac TSs, when asymmetry and harmonics exert a combined influence on the PUS, both disturbances must be analyzed together. In case the limits on these disturbances are exceeded, special measures must be undertaken, such as changing the power supply arrangements or installing symmetrizing equipment.

Voltage Flickers. Due to step changes of traction loads, voltage flickers (*VF*s) may be observed at the point of common coupling (*PCC*) of a TS, which influence other energy consumers. The limits of allowed VF are usually expressed as the maximum permitted repeated voltage change ΔU [%] as a function of frequency f [min^1], which may be specified by the PUS company as in Ref. 9 (for 38 kV lines):

$$\Delta U = 1.105 f^{-0.2275}\% \qquad (53)$$

or as suggested by the PUS company in Poland:

- For HV lines,

$$k = \begin{cases} 1.03 & \text{for freight wagons} \\ 1.05 & \text{for passenger coaches} \\ 1.1\text{–}1.15 & \text{for multiple traction units} \\ 1.2 & \text{for streetcars} \\ 1.3 & \text{for trolley buses} \end{cases}$$

- For MV lines,

$$\Delta U = \begin{cases} 2\% & \text{for} \quad 0.1 \le f \le 3\ \text{min}^{-1} \\ 1\text{–}2\% & \text{for} \quad 3 \le f \le 30\ \text{min}^{-1} \end{cases}$$

It is possible to recalculate the above values of ΔU for the corresponding permitted step changes in current load ΔI using the following formulas (for DC traction systems):

$$\Delta I = \frac{\Delta U \cdot U^2 \eta}{100 \cdot U_{DC}[X \sin\varphi + R\cos\varphi]} \qquad (54)$$

where

U = supply voltage,
U_{DC} = Dc voltage of the rectifier TS,
η = efficiency of the TS,
X, R = reactance and resistance of PCC (corresponding to a fault level),
$\cos\phi$ = load power factor (assumed lagging)

and then compare the results with the load profile of TS obtained from traction power supply system calculations.

Stray Currents. Rails that are used as a part of return current network are not perfectly isolated from the ties, ballast, and ground, and a significant part of the return current I flows to the TS through the ground and conducting elements buried in it [stray currents, I_{h} Fig. 27(a)]. In areas when rails are at higher potential than the surrounding ground (*anode zone* of rails), current flows out from the rails to the ground, while in areas where the ground is at higher potential than the rails (*cathode zone* of rails) currents return to the rails. If the return rails are connected to the negative busbar of the traction rectifier substation, the anode zone moves with the EV taking current, while the cathode zone is situated around connections of return feeders to rails [Fig. 27(a)].

Stray currents cause electrochemical corrosion of metallic structures buried in the ground, because they operate as galvanic cells, the ground being an electrolyte, and the ions (charged atoms) of metal move away from the structures (mainly in cathode zones of rails). The mass of eroded metal is governed by Faraday's law.

The return-path traction current can be described using the resistance per unit length of the rails, r_{R} [Ω/km], and the resistance from the rails to the ground, $r_{\mathrm{R-G}}$ [Ω km] or conductance $g_{\mathrm{R-G}}$ [S/km], $g_{\mathrm{R-G}} = 1/r_{\mathrm{R-G}}$ [Fig. 27(b)]. The flow of current $dI_{\mathrm{R}}(x)$ from an elementary section dx of rails is shown in Fig. 27(c), where

$I_{\mathrm{b}}(x)$ = stray current at distance x from the EV
$I_{\mathrm{r}}(x)$ = current flowing in rails at distance x from the EV
$U_{\mathrm{R-G}}(x)$ = voltage between rails and remote ground at distance x
$dU_{\mathrm{RG}}(x)$ = change of voltage between rails and remote ground at an elementary section dx of rails

The equations are as follows:

$$dI_{\mathrm{R}}(x) = -\frac{1}{r_{\text{R-G}}} U_{\mathrm{R}}(x)\,dx \qquad (55)$$

$$dU_{\mathrm{R}}(x) = -r_{\mathrm{R}} U_{\mathrm{R}}(x)\,dx \qquad (56)$$

where the minus sign means that for positive values of $U_{\mathrm{R}}(x)$ and dx the current I_{R} in the rails decreases [Fig. 27(c)]. Solving the above equations, we get

$$U_{\mathrm{R}}(x) = C_1 e^{\alpha x} + C_2 e^{-\alpha x} \qquad (57)$$

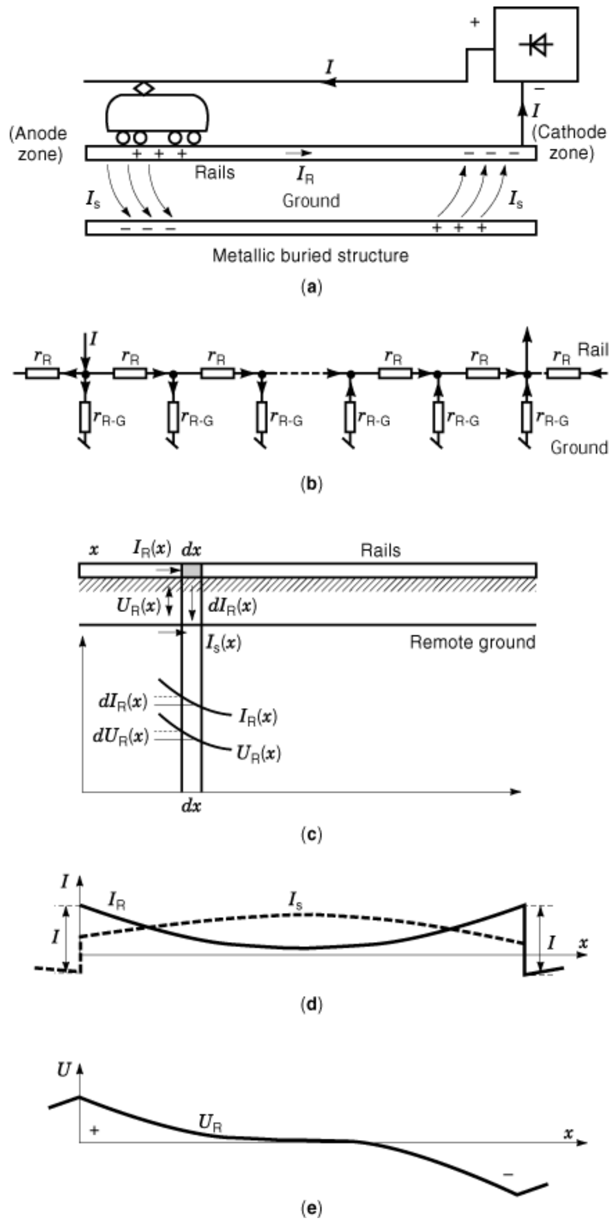

Fig. 27. Stray currents in dc traction: (a) scheme of stray current flow with one EV receiving current I from one rectifier substation, (b) equivalent dc circuit, (c) current flow away from elementary section dx of rails, (d) rail current I_R and stray I_s current along the section, (e) rail voltage U_R along the section.

$$I_R(x) = -\frac{1}{R}C_1 e^{\alpha x} - C_2 e^{-\alpha x} \qquad (58)$$

$$I_S(x) = I - I_R(x) \qquad (59)$$

where C_1 and C_2 are integration constants, and

$$\alpha = \sqrt{\frac{r_R}{r_{R\text{-}G}}} \quad \text{propagation constant} \qquad (60)$$

$$R = \sqrt{r_R r_{R\text{-}G}} \quad [\Omega] \quad \text{characteristic resistance} \qquad (61)$$

Graphs of U_R, I_R, and I_s for unilateral supply of one EV taking current I are shown in Fig. 27(d) and (e). Usually the supply schemes, especially for a streetcar return network, are more complicated, utilizing a distributed return network. One then applies *superposition method*, using the above equations for each load, or else *matrix methods*. In order to eliminate stray current migration from rails, the following remedies should be considered:

- Lowering the voltage between rails and ground (by lowering of the resistance of rails or shortening the distances between traction substations)
- Proper configuration of return feeder cables, higher system voltage, open bonding of the catenary support structures [Fig. 20(a)], or grounding with isolation of the foundation from the earth [Fig. 20(b)]
- Increasing the resistance between rails and ground (depending on the type of ties and ballast)—in some circumstances this may cause high step or contact voltage between rails and ground), or providing a special path for return current separated from the running rails
- Isolation and sectioning of installations buried in the ground
- If an area (e.g., in a tunnel or near the sea) is especially vulnerable to stray currents (which may assessed by measurements or calculations), special measures are to be undertaken as follows: *cathodic protection* with an imposed current (which decreases the voltage between the rails and the protected installation in the anode zone of the rails, decreasing the stray current flow), or *electrical drainage* (equipotentialization between the rails and the protected installation in the cathode zone of the rails).

Electromagnetic Compatibility of Electrified Ground Transport Systems

As may be seen in Fig. 25(f), an EGTS is a complex system with subsystems that, in order to operate safely and reliably, have to fulfil electromagnetic compatibility requirements. The difficulties in achieving compatibility result from the different categories of subsystems: the high-power supply system and EVs are in the megawatt and kilovolt range, while low-power signaling and control systems operate the range of milliamperes and volts. Another problem is the operating frequency bands of installations. Even if different subsystems operate within separate frequency ranges, there may appear harmonics, which can cause disturbances that are transferred from one subsystem to another by capacitive, conductive (galvanic), and inductive coupling and wave phenomena. For safety reasons the voltages transferred from power circuits to conducting structures of an electrified railway have to be kept below certain limits [the maximum allowed longitudinal continuous induced voltage

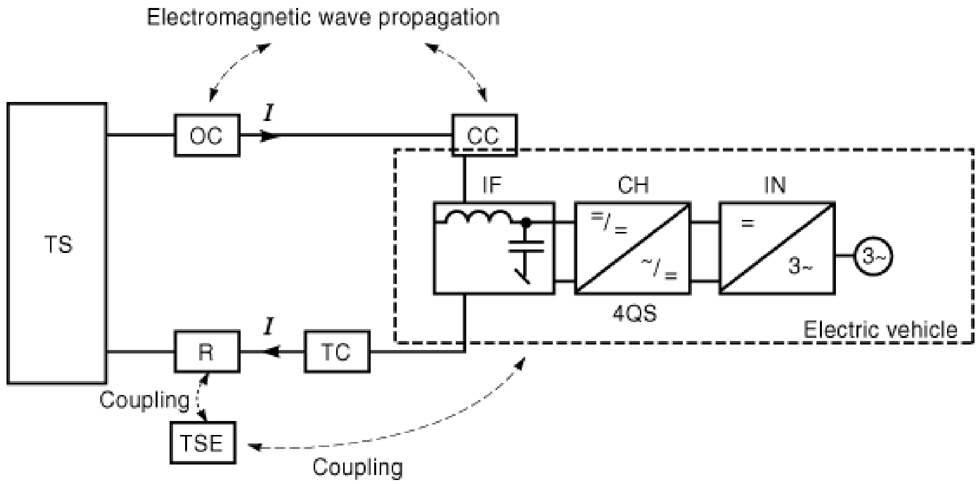

Fig. 28. Disturbances in electrified transport system and neighboring technical infrastructure: TS, traction substation; R, return network; TC, traction circuits; OC, overhead catenary; CC, current collector; IF, input filter; CH, chopper; 4QS, four-quadrant converter; IN, inverter.

to ground (at the fundamental system frequency) 60 V; in short-term fault conditions it is 430 V (2, 7)]. A special ground wire is installed, to connect support structures and protect against SC or isolation breakage, by bonding to the rails [Fig. 20(a,c)], or double isolation is used [Fig. 20(b)]. Voltage drops and harmonics flowing in rails (conductive coupling) may cause the following malfunctions of track circuits:

- *Right-side failure.*Safe, but causing disturbances in traffic when unoccupied track is signaled as occupied
- *Wrong-side failure.*Dangerous when a block of track with a train on it is signalled as unoccupied

According to the type of traction circuit (*TC*) used, limits on harmonic currents in rails are imposed. In case disturbances exceed the limits, special measures should be undertaken to reduce disturbances at their source (using filters, or changing the equipment or its mode of operation) or to make the TC immune from them.

The main source of disturbances in EGTSs are (Fig. 28):

- *TS.* Dc traction rectifier substations (dc side voltage harmonics)
- *Power Electronic Converters of the EV.* Dc-dc converters [choppers (CH) at fixed frequency] or ac-dc converters (4QS); inverters (IN) supplying ac motors (with frequency of operation variable from 2 Hz to 120 Hz)
- *Current Collectors* (*CC*). Radio-frequency harmonics
- *Transients.*starting of EV, faults in catenary

The current *I* delivered from TS to EV is composed not only of *characteristic harmonics* (typical due to type of equipment used) but also of *noncharacteristic harmonics* (due to faulty operation of converters) or asymmetry and *sideband harmonics* (due to intermodulation of harmonics imposed by different sources). The catenary (OC) and return railway current network (R) in Fig. 28 show frequency dependence of their parameters, which, together with the dc side filter of the rectifier substation (in dc power supply systems) and the input filter (*IF*) of the EV (which by moving along the line changes the parameters of the energy source), create various reso nant circuits. In ac systems resonance may cause significant catenary overvoltages (more than twice the nominal voltage) (16).

The level of disturbances in telecommunication lines, which must be kept below the specified limits, may be assessed using the psophometric current I_{P} (or voltage U_{P}), defined as (2)

$$I_{\mathrm{p}} = \sqrt{\sum (I_n \omega_n)^2} \tag{62}$$

where

$I_{\mathrm{n}}(U_{\mathrm{n}}) =$ nth current (voltage) harmonic

$\omega_{\mathrm{n}} =$ weighting factor for the nth harmonic

According to Refs. 2 and 7, the limits on psophometric voltage are: in public phone cables 0.5 mV to 1 mV; in railroad phones 1 mV to 2 mV (cabled) and 5 mV (open-wire). On railroads limits may be imposed on the psophometric value of the harmonic component of dc side voltage, as high as 0.5% of the nominal voltage in Poland or 10 V in Italy (both for 3 kV dc systems).

Trackside equipment (*TSE*) (Fig. 28) is also vulnerable to inductively coupled disturbances caused by current flow in rails and on-board power circuits of an EV. Modeling and simulation methods are widely applied for prediction of disturbing interference effects and their elimination at the design state of an ETGS (6,7,8,9, 11), while for installations compatibility tests should be undertaken according to local standards and codes (2, 9,10,11, 17, 18).

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ADAM SZELAG
LESZEK MIERZEJEWSKI
Warsaw University of Technology