AC and DC Railway Power Systems for Electric Traction: One Purpose – Many Solutions

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Photo: Deutsche Bahn AG / Volker Emersleben

AC and DC Railway Power Systems for Electric Traction: One Purpose – Many Solutions

Introduction

A bit of history

„Electric Machinery 101“

Traction power systems:
DC – AC – Specials

Technology and key components:
Controls – Substations – Contact Systems

Conclusion & outlook

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Introduction

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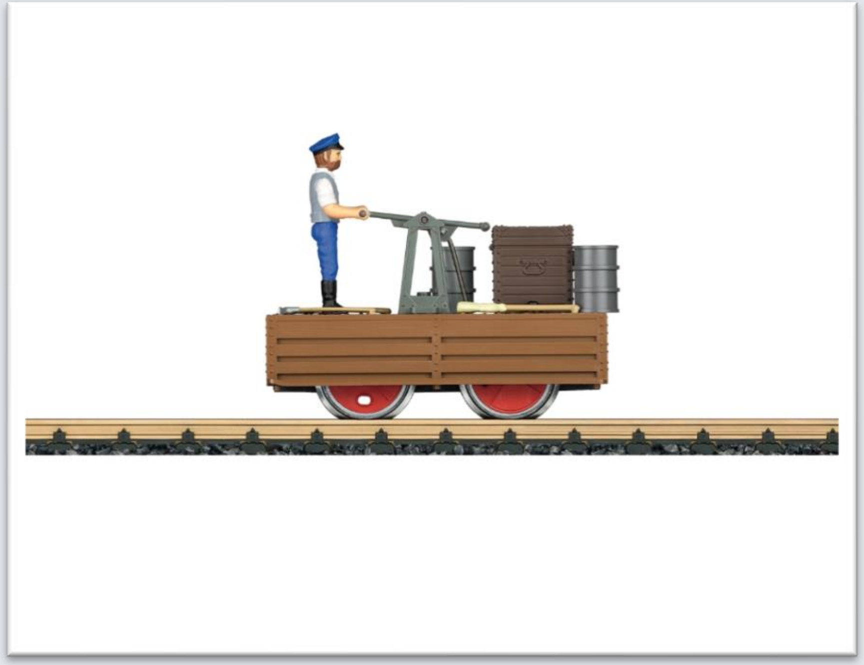
Energy conversion into traction effort: on-board vs. infrastructure

- Conversion in moving part



- Conversion in fixed part

Steam

Diesel

Electric

Hydrogen

Pulley

MagLev

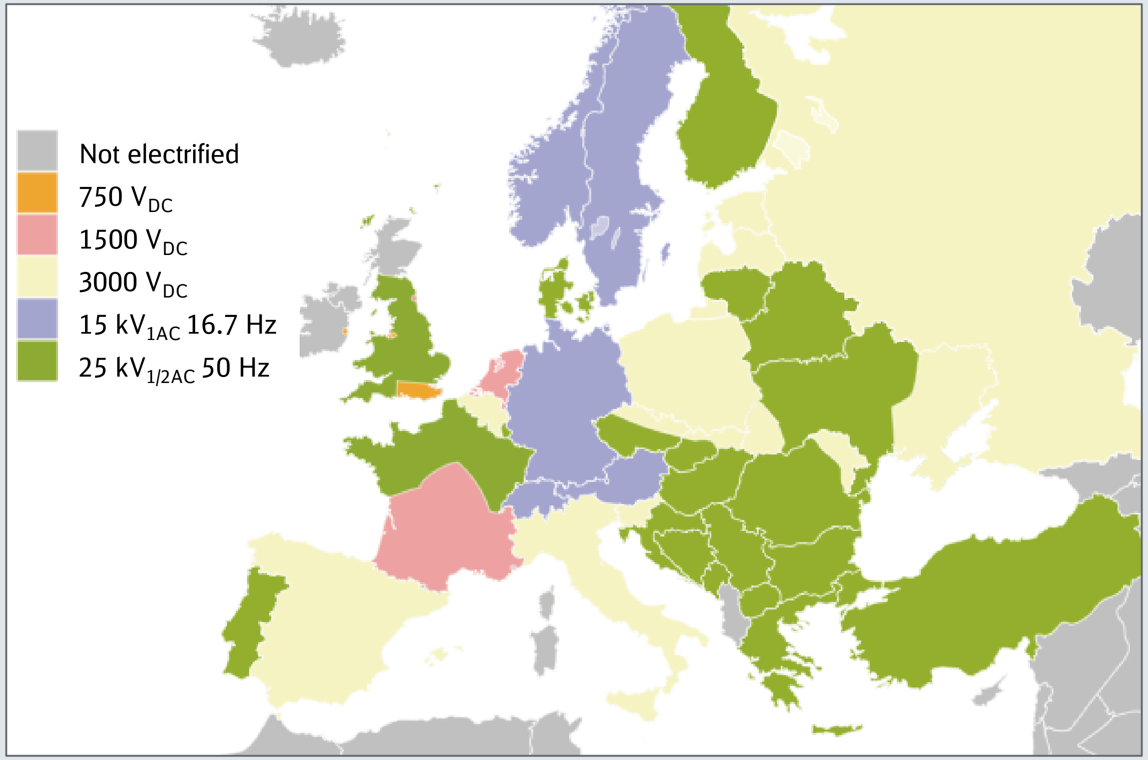
Hyperloop

Pictures: www.maerklin.de; www.pastorini.ch; www.bahnbilder.de

Introduction

Fundamental regional differences in voltage, frequency, polarity, contact system…

- Mainline electrification standards in Europe



- Mass transit: selected systems worldwide

	DC Voltage	AC Voltage
Overhead Catenary System	Tram Vienna (+600V); Stuttgart Stadtbahn (+750V); Budapest HÉV (+1000V); Buenos Aires Subway (+1500V); Tel Aviv Red Line (+1500V); Pyongyang Local RR (+3000V)	New Jersey Transit (12.5kV 25Hz); British Columbia RR (50kV 60Hz); Jungfraubahn Mountain RR (1125V 3~ 50 Hz); Karlsruhe TramTrain (15kV 16.7Hz)
Rigid Conductor Rail	MBTA Boston Red Line (+600V); London Underground (+420V / – 210V); Moscow Metro (+750V); S-Bahn Berlin (–750V); S-Bahn Hamburg (+1200V)	SkyTrain Dusseldorf (400V 3~ 50Hz)

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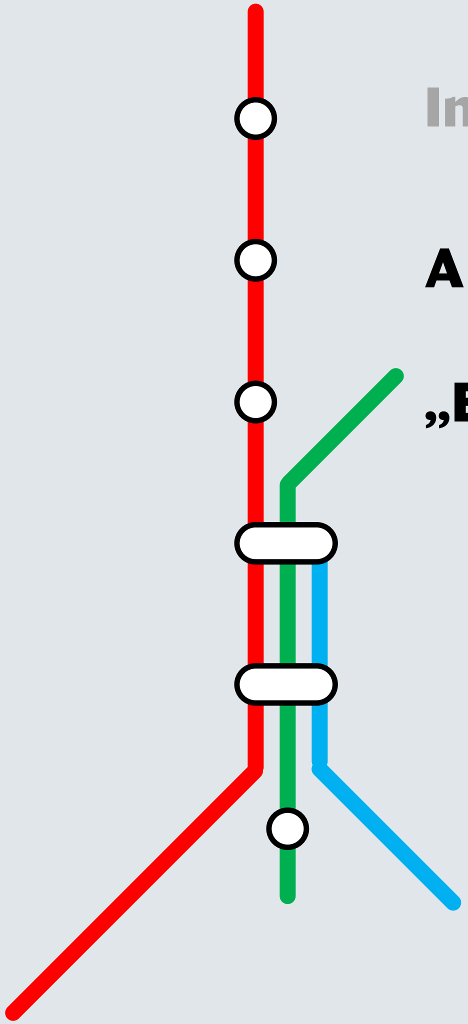


Introduction

A bit of history

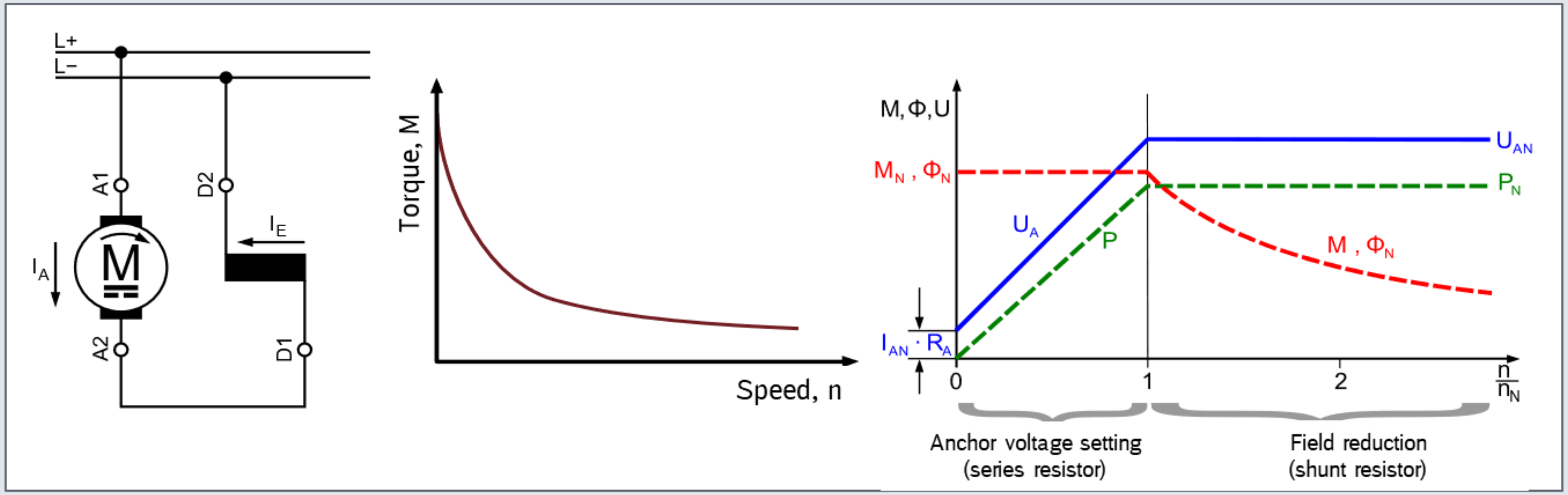
„Electric Machinery 101“

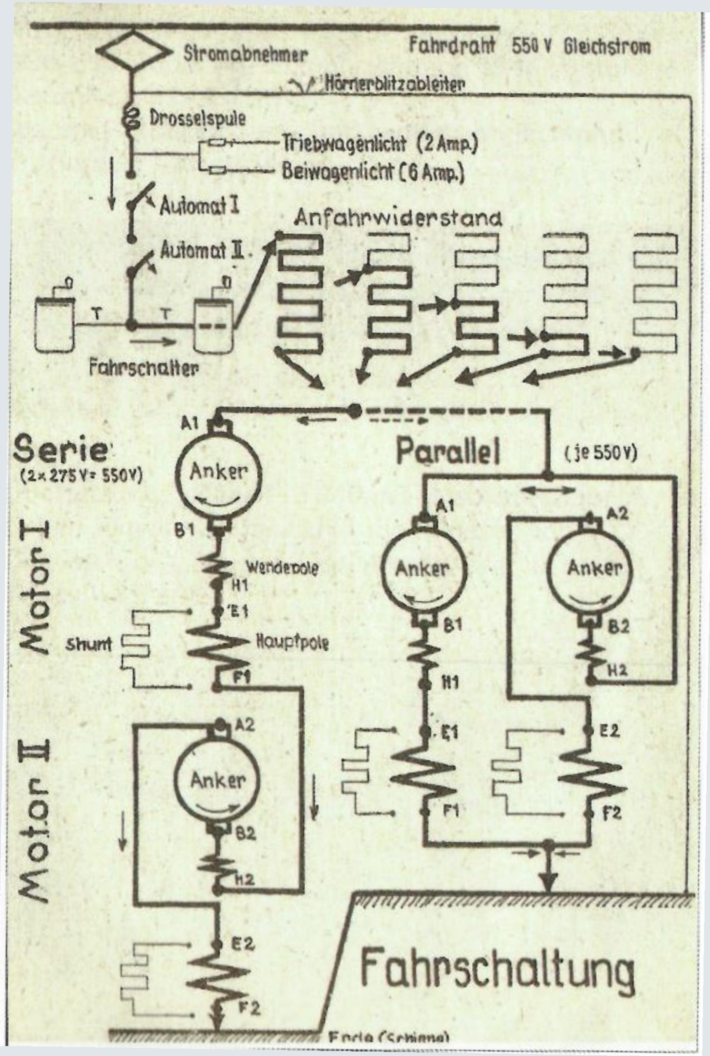
A bit of history, and a refresher “Electric Machinery 101”

Series-connected DC motor was the original railway engine of choice

- Only series-connected DC motor has torque/speed profile compatible with traction power needs

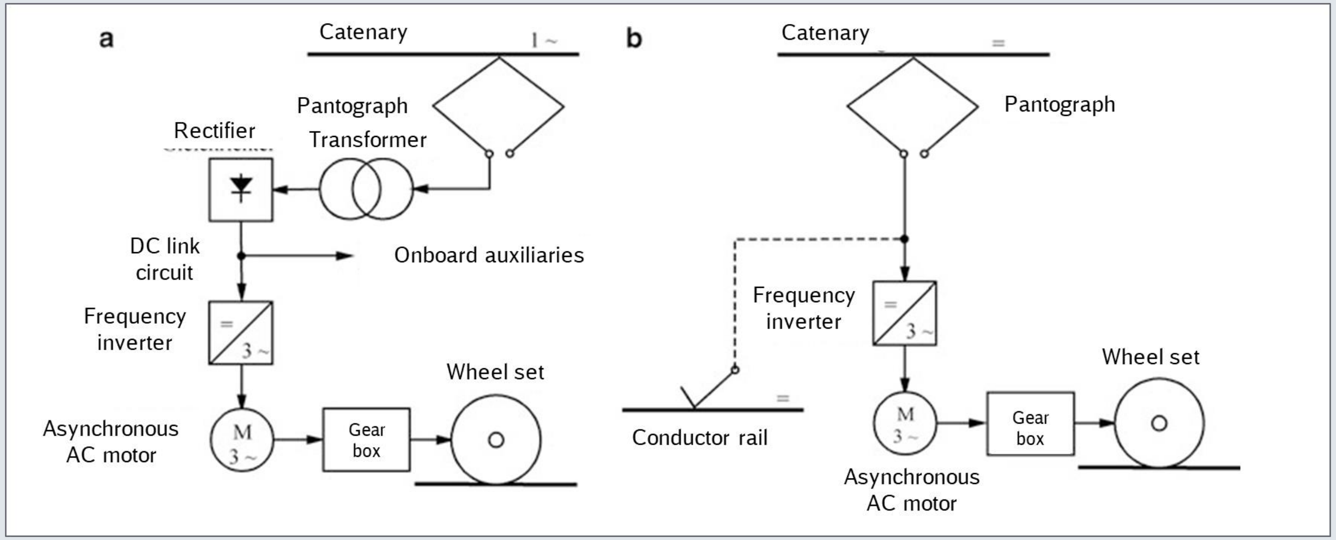
- Characteristics of torque (M), flux (Φ), voltage (U), power (P) vs. speed (n/nN) characteristics controlled by series and shunt resistors (Example: tram Zwickau, 1910)





A bit of history, and a refresher "Electric Machinery 101"

Maintenance-friendly asynchronous AC (universal) motor allows higher voltages



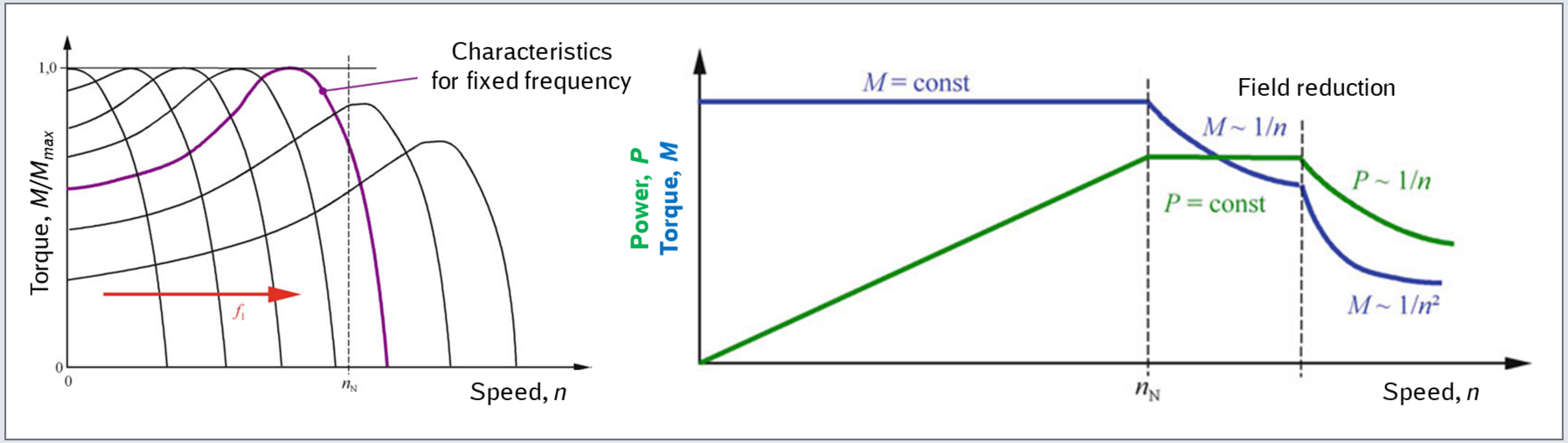
Optimization problem:

- Higher voltage → lower losses
- Higher frequency → higher losses
- Lower frequency → higher transformer weight

→ **Reduced frequency,**
e.g. ⅓ 50 Hz = 16⅔ Hz, 25 Hz

Block diagram for rail vehicles with asynchronous motor
***a**: AC supply;* ***b**: DC supply*

Variable-frequency drive "mimics" torque-speed characteristic of DC motor



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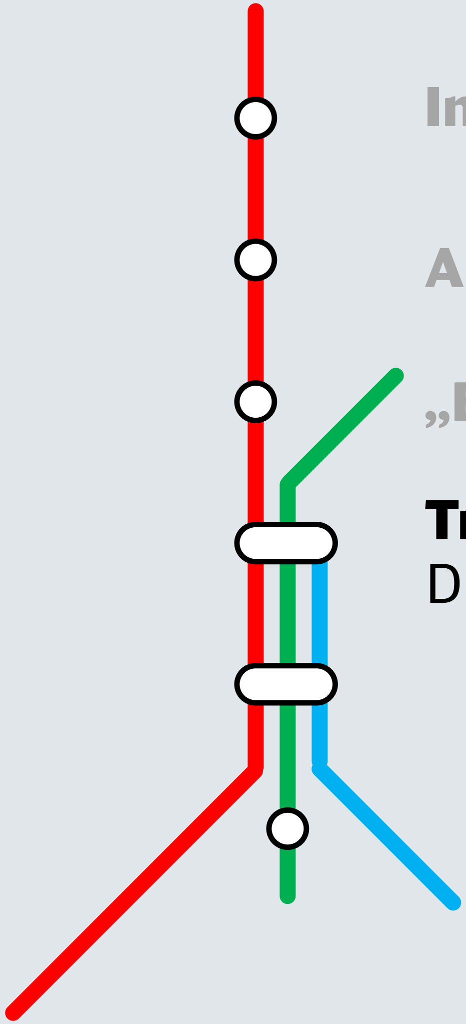

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„Electric Machinery 101“

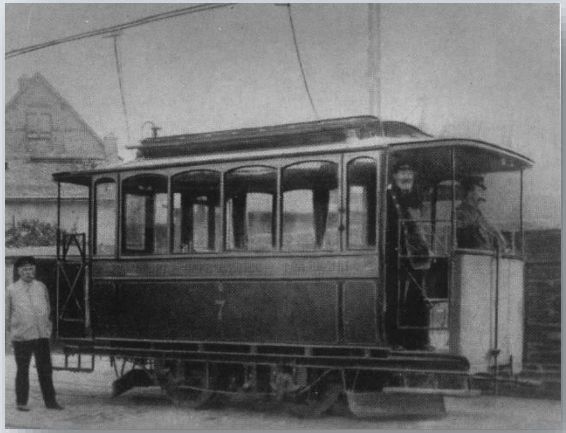
Traction power systems:
DC – AC – Specials

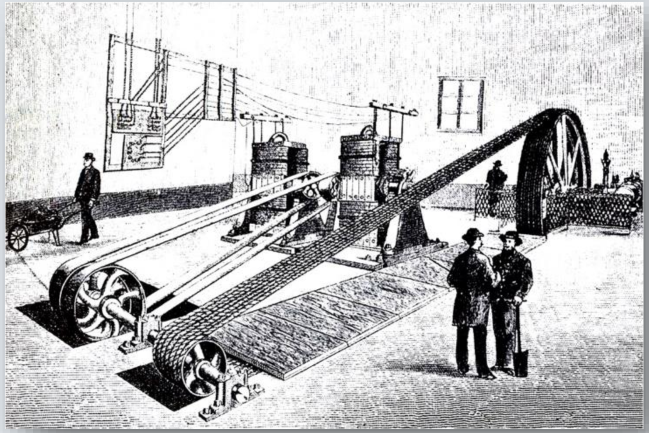
Traction Power Systems

DC voltages below 1000 V cover most Light-Rail Transit (LRT) systems worldwide

DC systems below 1000 V

- First electric trains operated at 150 V_{DC} / 300 V_{DC}
- IEC 60038:2009 defines "low voltage" as <1000V
- 750 V_{DC} is most widely-used power system for trams / streetcars, trolley busses, metros





Frankfurt-Offenbach tram and substation, 1870's at 300 V_{DC}

Munich tram and substation, 2000's at 750 V_{DC}

Traction Power Systems

DC voltages above 1000 V serve for Mass Rapid Transit (MRT) and mainline

DC systems at 1500 V

- 1500 V_{DC} highest “low voltage” per IEC 60038:2009 in many jurisdictions
- Typical for most heavy subways / metros, e.g. Tel Aviv Red Line

Tel Aviv Redline, 2020’s at 1500 V_{DC}

DC systems at 3000 V

- Usually for mainline only, including freight lines and mining trains

High-speed trains in Spain and Russia, 1990’s at 3000 V_{DC}

Traction Power Systems

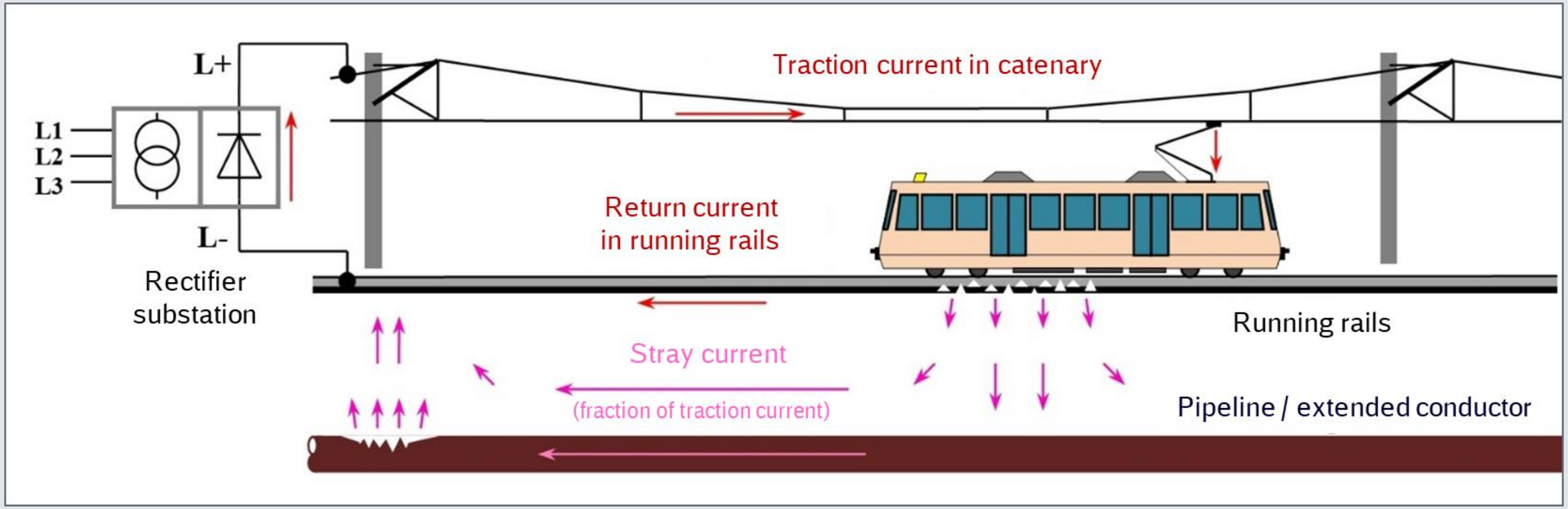
DC traction: Stray currents can, if not properly controlled, cause corrosion problems

Electrolytic corrosion

- Cathodic corrosion is uncritical
  ($2\ H_2O + O_2 + 4e^- \rightarrow 4\ OH^-$)
- Anodic corrosion can be problematic: one Amp can dissolve almost 10 kg of steel per year
  ($2\ Fe \rightarrow 2\ Fe2+ + 4e-$; $C_{Fe} = 9.1$ kg/A·yr)

Remedies

- Insulation of running rails from ground
- Continuous supervision of insulation resistance
- Distance between rail and other installations
- Active cathodic protection of external conductors



Traction Power Systems

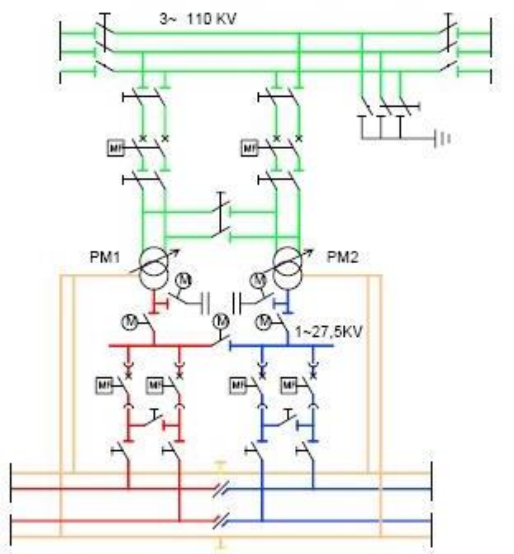
Single-phase AC voltages is the method of choice for (new) mainline electrification

AC systems at reduced frequency

- 15 kV 16.7 Hz is standard “ever since” in Germany (+AT/CH/NO/SE).
- Requires dedicates generation and transmission (±55 kV 16.7 Hz)

AC systems at standard frequency

- Standard for new installations, typically 25 kV 50(60) Hz
- “Rolling V-scheme” to minimize unbalance when connecting to HV public grid

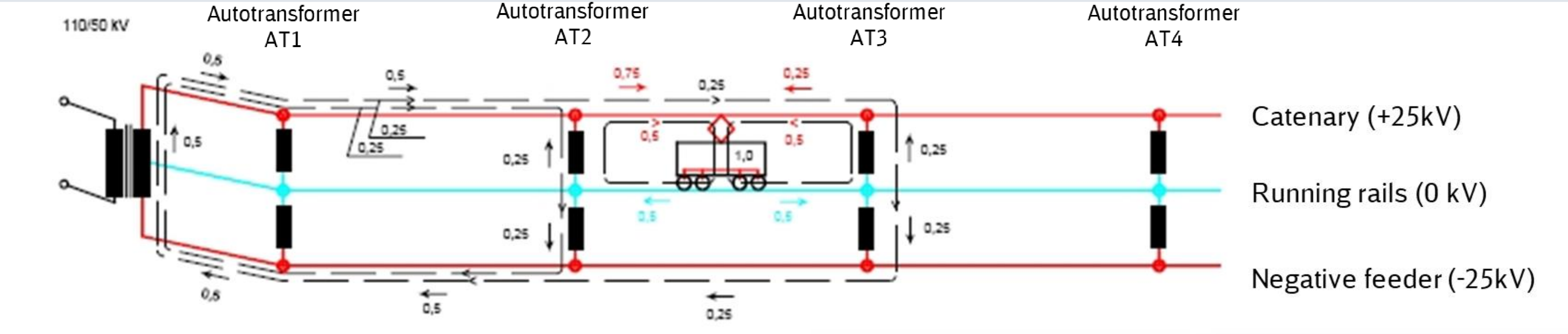


Deutsche Bahn, 1900’s ~today at 15 kV$_{AC}$; Transmission grid at 110 kV$_{AC}$ 16.7 Hz

Beginning of electrified era in Israel (14-Dec-2017) at 25 kV$_{AC}$ 50 Hz

Traction Power Systems

Two-phase AC systems allow for even larger spacing of substations



Autotransformer scheme

- Autotransformers typically used for long high-speed lines (FR/US/CN...)
- Requires separate conductors for catenary and negative feeders (±25 kV 50Hz)
- Requires AT stations every 5...10 km and sophisticated protective relaying schemes

TGV Overhead Catenary System (France); AMTRAK AT station (USA)

Traction Power Systems

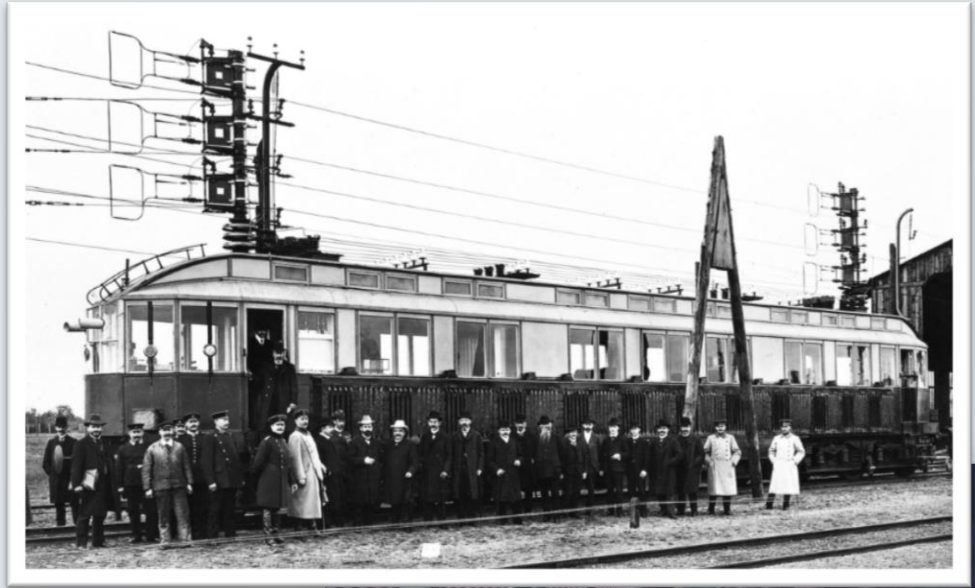
Three-phase AC systems play no role anymore – may change with wayside conversion

Early attempts to increase power

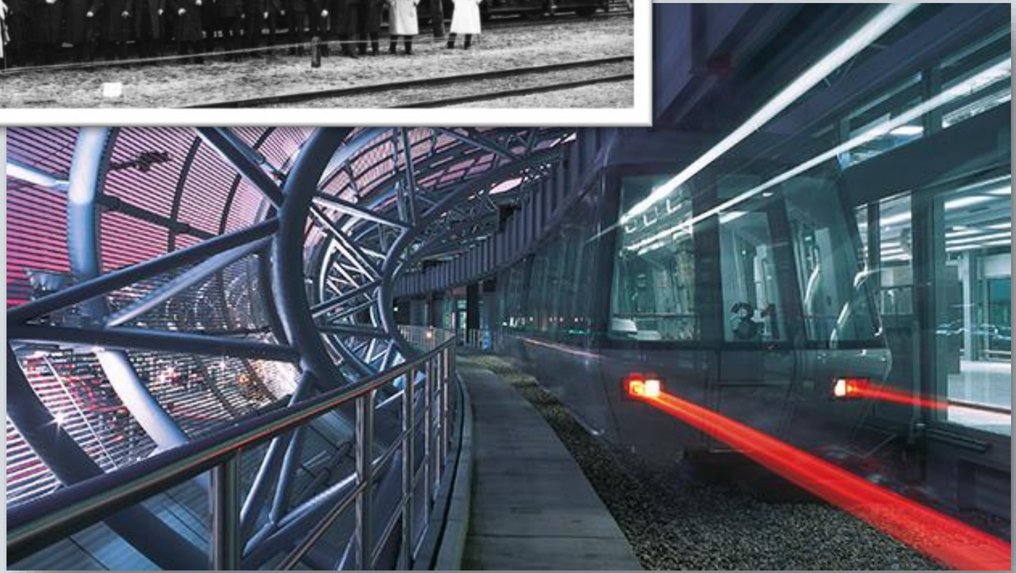
- German army's corps of engineers: 3AC transmission to world's first train going >200 km/h (1903)
- 3AC 400 V (standard industrial supply) through current collector rails to early "people movers" (AEG, 1970's)

Wayside power conversion

- On systems with active components in the infrastructure (MagLev, HyperLoop), obviously three-phase MV power intake is required (and possible!) for electromagnets



Royal Prussian Military Railroad (1903)



SkyTrain Dusseldorf airport (1970~)

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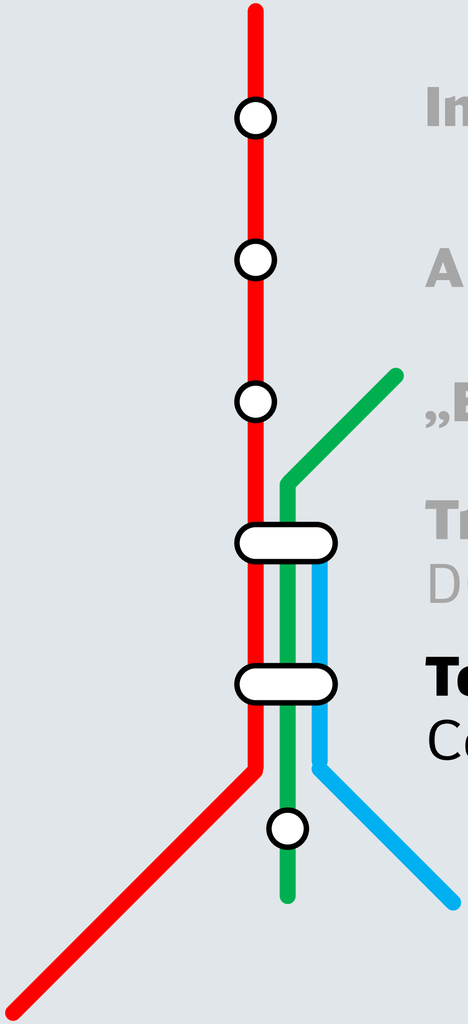

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Traction Power Technology and Key Components

All TP facilities all remotely controlled and monitored

DB Energie network dispatch and control center

- Operations & Control Centers (OCC) either integrated or dedicated for power grid
- "Predictive Maintenance" through sensors and artificial intelligence

Traction Power Technology and Key Components

Outdoor or hybrid (containerized) substations mostly for mainline / AC systems

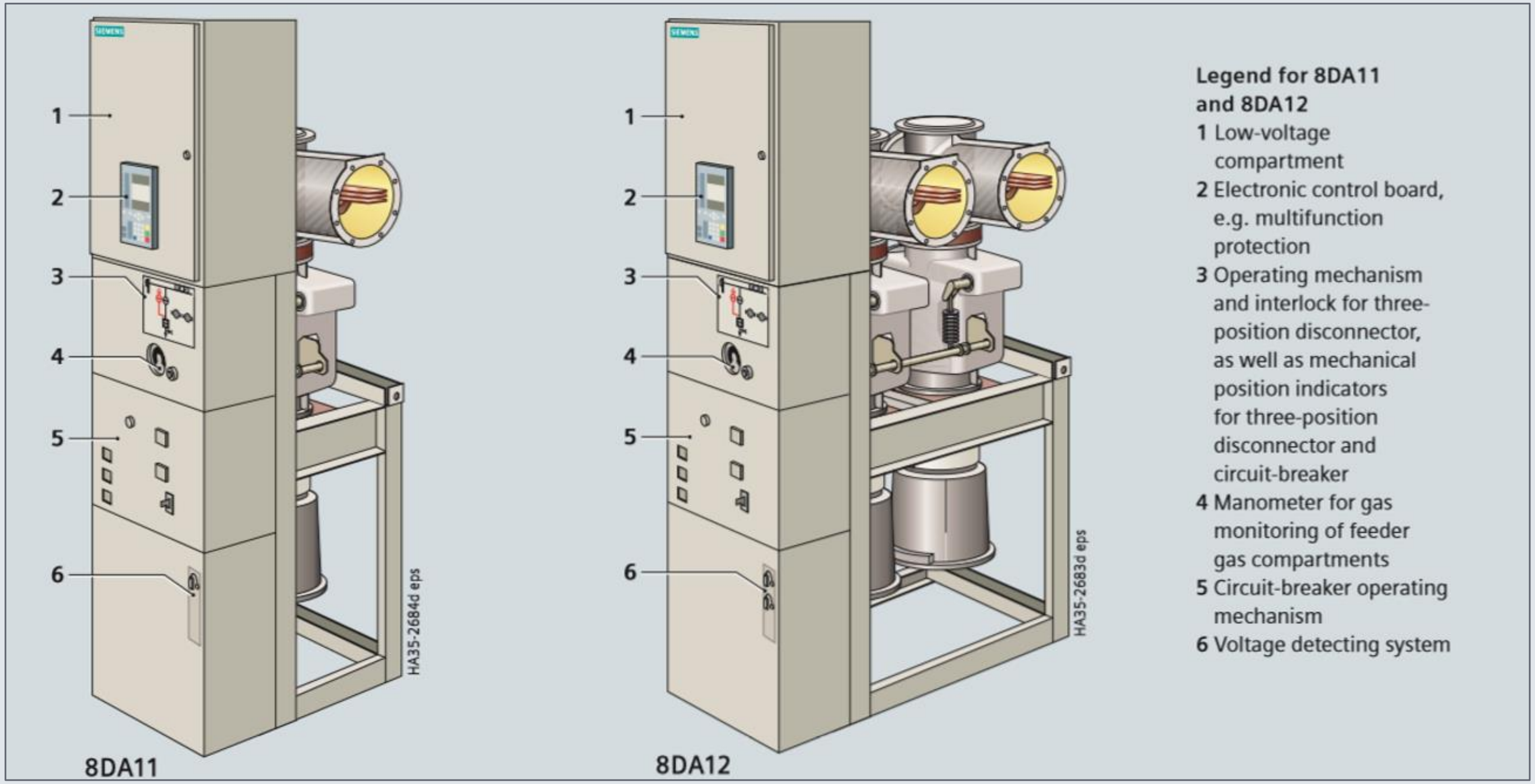
2x25 kV traction transformer (left) and outdoor switchgear (right) in Indian Railways

- Robust, field-proven technology from conventional HV switchyards
- Large space requirements, emission/immision needs to be considered
- Susceptible to ingress and vandalism

Traction Power Technology and Key Components

Outdoor or hybrid (containerized) substations mostly for mainline / AC systems

- Containers accommodate switchgear, controls & protection
- Transformer and overhead line intake & outgoing remain outdoors



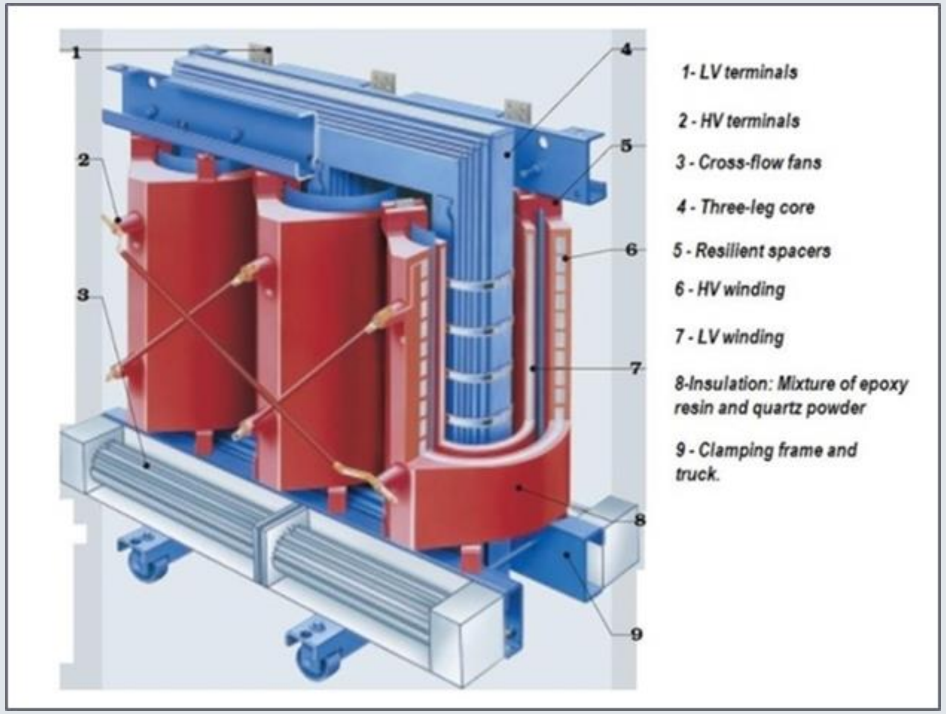
Numerical transformer differential protection and operation relay
Source: ABB

1x25(15) kV and 2x25 kV gas-insulated switchgear (width: 600 mm)
Source: Siemens

Traction Power Technology and Key Components

Indoor substations mostly for mass transit / DC systems

- Transformers and power cables:
  low smoke / zero halogene (LSZH)

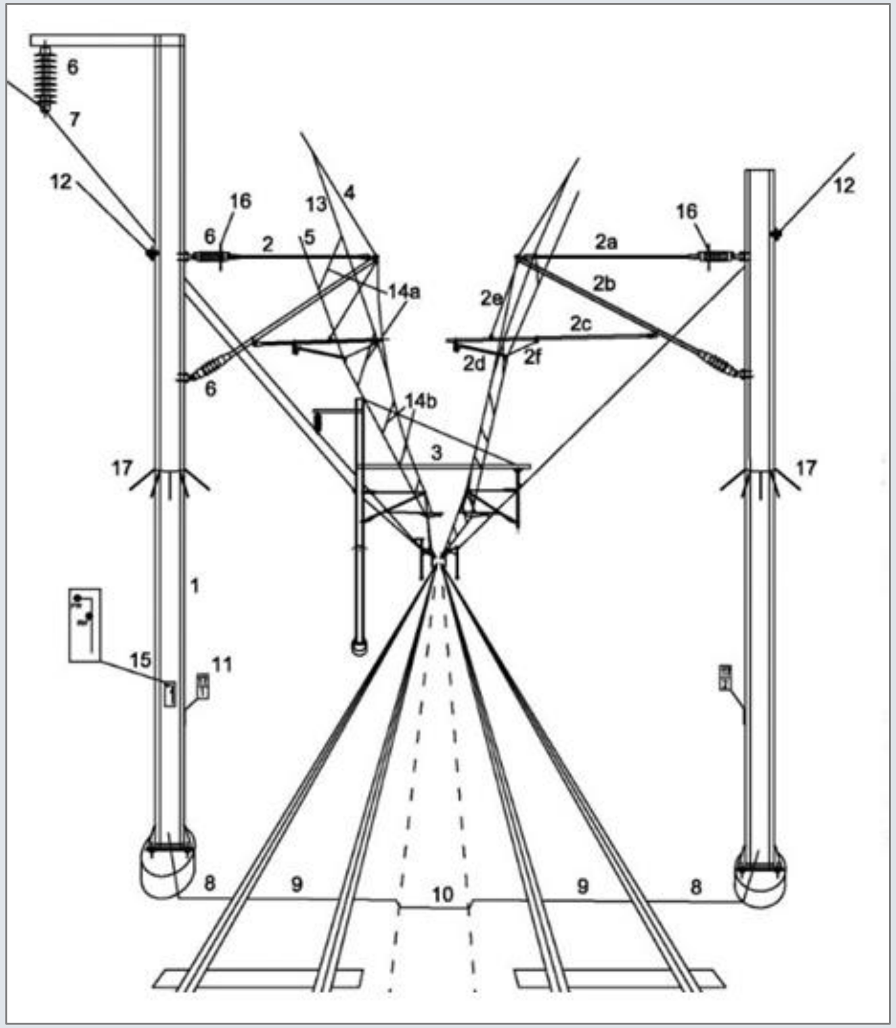


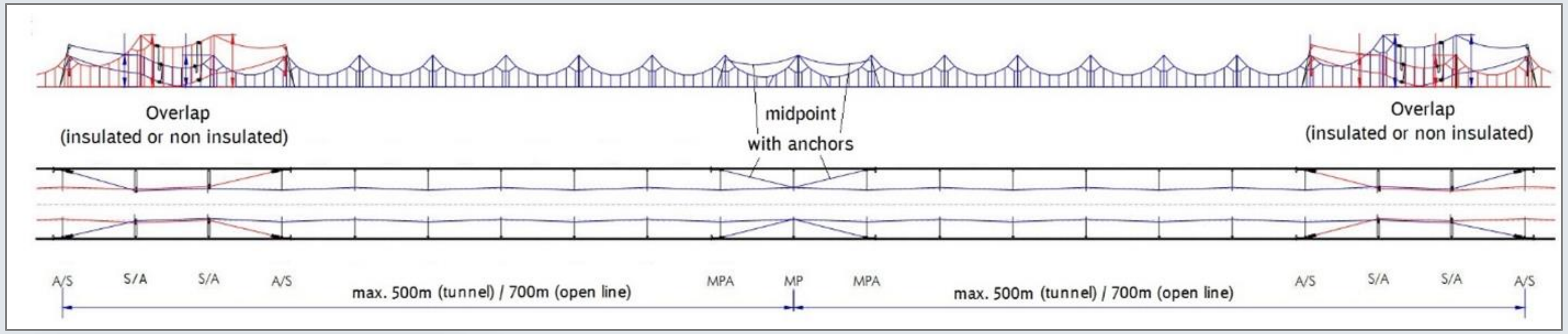
Rectifier, DC switchgear, DC circuit breaker
Source: Sécheron

- Silicone rectifiers: six-, <u>twelve-</u>, twenty-four-pulse
- Metal-clad switchgear with DC circuit breaker trucks
- Circuit-breaker to withstand up to 8,000 A and interrupt up to 180 kA without current-zero!

Traction Power Technology and Key Components

Overhead Contact System (OCS)





OCS scheme as used for Israel Railways

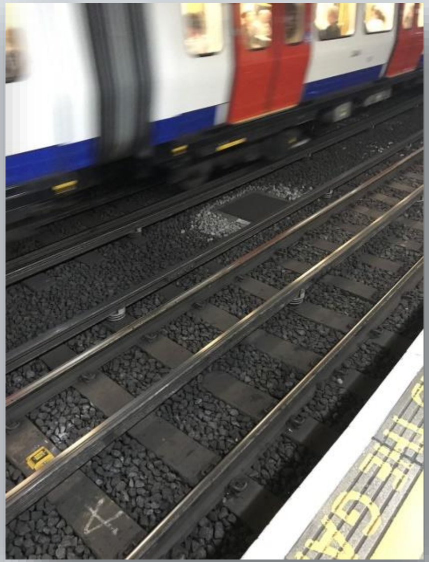
- Interface between pantograph and contact system is magic, involving many disciplines
- Autotensioned system provides constant pulling force and OCS dynamics independent from temperature
- Contact wire in “zig-zag” to even out wear on pantograph’s carbon strips

Traction Power Technology and Key Components
Conductor Rail System

Conductor Rails (“Third” and “Fourth” Rail)

- Typically aluminum/steel compound rails (Vienna, left) for collector shoe picking up from below (Berlin)
- Steel conductor rails still in use (Tokyo) and used as “third/fourth” rails (London, right)



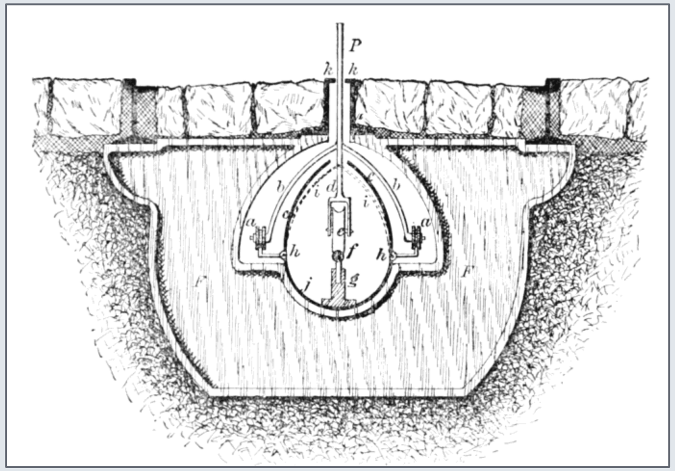



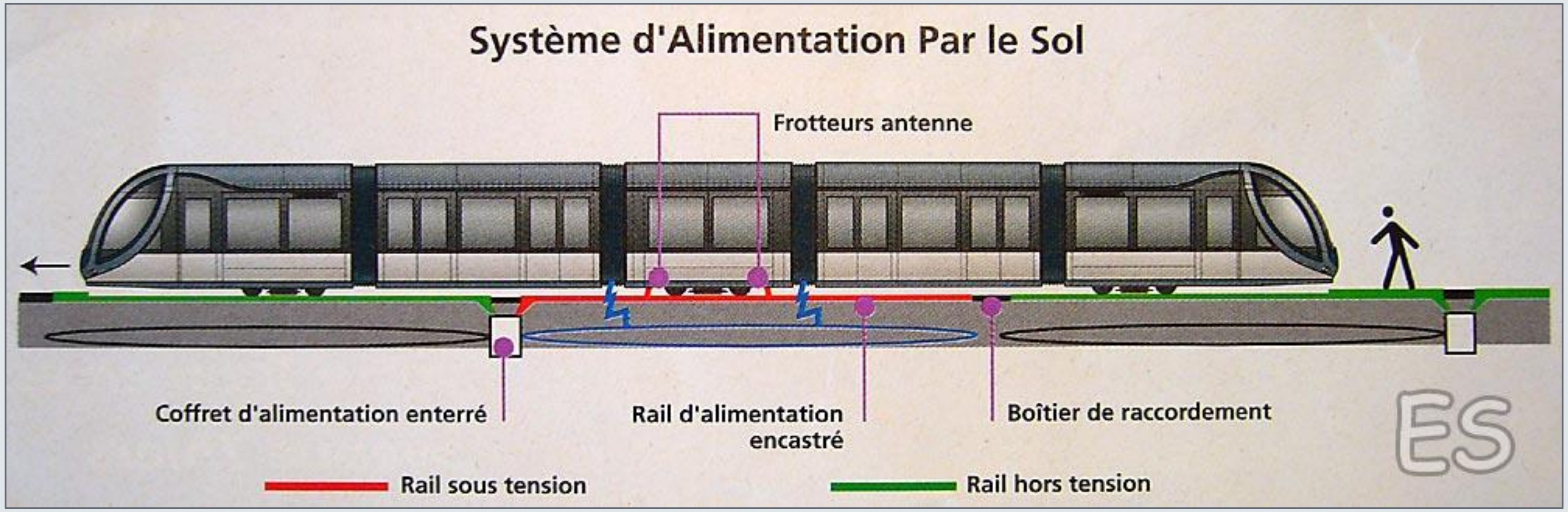
Traction Power Technology and Key Components

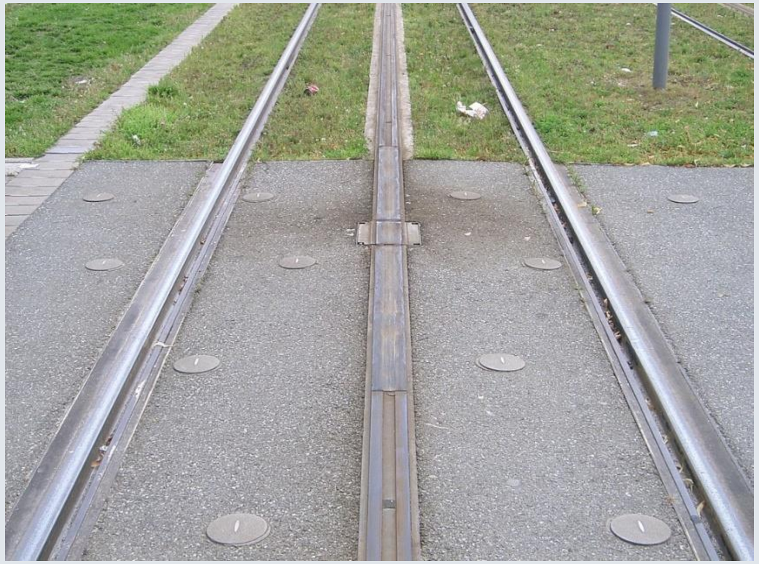
Alternatives without visible contact line or third rail are (still) a niche

Embedded conductor rails

- Idea originally documented in 1899
- Innorail (later Spie/Alstom) developed system with energized sections only safely underneath train







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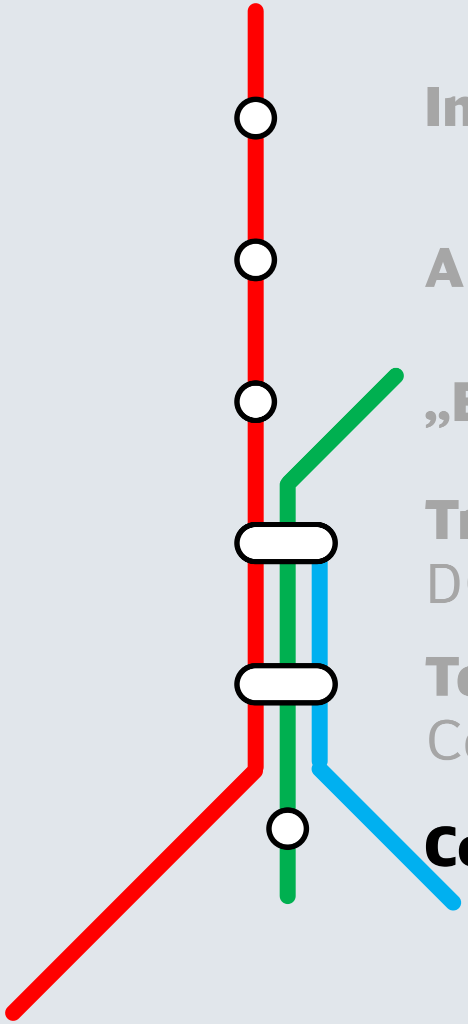

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Let’s shape the Railways for Tomorrow!

Source: fotolia/den-belitsky

Thank you for your attention!

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