Overhead line (OHL) systems for high-speed railway lines: considerations

The demands made on traction power supply systems for the operation of electric trains have increased continually due to a rise in performance and speed of trains operating on high-speed and high-capacity railway lines. This article looks at a number of considerations as regards overhead line (OHL) systems for high-speed railway lines.

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OHL POWER SUPPLY SYSTEMS — CONTACT WIRE CONSIDERATIONS

In Europe, the most commonly adopted traction power supply systems for mainline and regional railway lines are:

- — *15 kV, 16.7 Hz AC systems:* in this case, the traction power that is collected from the OHL system is generated primarily in railway-owned power plants or via central converter stations with transmission into the railway-owned power supply network;
- — *25 kV, 50 Hz AC systems:* in this case, the traction power is collected directly from the three-phase public power supply network. Single-phase traction current loads cause asymmetries in the phase voltages and current loads of the three-phase network, which would have an unacceptable effect on all consumers in the network. Therefore, in order to ensure a quasi equal current loading, railway substations are connected only to three-phase power supply networks that have a high short-circuit rating and, in line with common practice, alternately single-phase to the outer conductors (L1-L2, L2-L3 and L3-L1 – see Fig. 1), and because of technical-historical reasons;
- — *1.5 kV or 3 kV DC systems.*

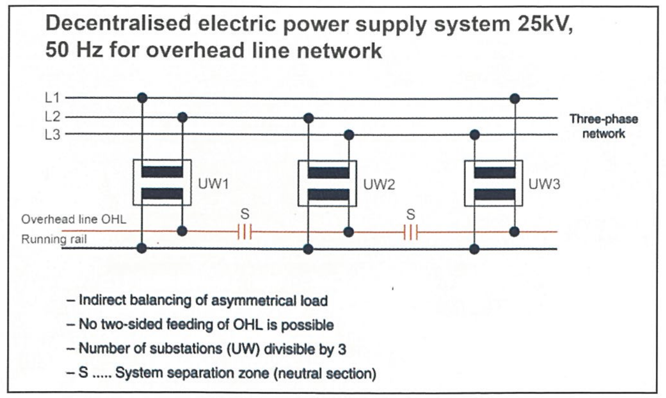


Fig. 1: Example – power supply of OHL system from three-phase networks (own illustration based on Chart 23 in [1])

The contact wire voltage must be kept within limits so that, firstly, the installations do not become damaged and, secondly, the performance of the traction units can be fully utilised. In TSI Energy and EN 50388, a quality index is defined by, for instance, the "mean utilisable voltage" at the pantograph. The OHL operating current is determined, amongst others, by train speed, train weight, train frequency, and gradients due to topographical circumstances.

Contact wire material

The contact wire has to transfer the current to the traction units faultlessly, whilst maintaining continuous electrical and mechanical contact with the pantograph in all train speed ranges. Even at standstill, a reliable current transfer has to be ensured. Additional tasks handled by the contact wire are the acceptance and return of braking energy from the traction units to the substation or its transmission to other trains, and the supply of energy to auxiliary consumers (e.g. train pre-heating systems, turnout heating systems, etc.).

The contact wire needs to have an adequate current-carrying capacity, a high electrical conductivity and tensile strength, as well as a resistance to heat, corrosion and wear. Therefore, instead of hard-drawn electrolytic copper, copper-based alloys with alloying additions, such as silver (CuAg 0.1), tin (CuSn 0.4), magnesium (CuMg 0.5), chromium, etc., are increasingly used to further improve the thermal and mechanical tensile strength of the contact wire.

Contact wire cross-section

When using alloying additions of magnesium or tin, the electrical conductivity of the contact wire drops by up to 30-40%, whilst its tensile strength (minimum breaking load) increases by about the same amount. A high tensile strength of the contact wire allows a nominal tensile force of currently up to about 38 kN. Contact wire materials of high tensile strength exhibit a lower wear rate in operation.

As per EN 50119, the mechanical design of OHL systems must also take into consideration factors such as temperature, abrasion, coating with ice, wind loading, and efficiency of the tensioners, etc. EN 50149 specifies standards for contact wire cross-sections, cross-sectional shapes, materials and strength data, electrical characteristics, current-carrying capacity, as well as resistance to heat, etc.

In EN 50119 and EN 50149, special test procedures for optimisation and evaluation of the contact wire production and OHL installation processes are prescribed, for instance as regards bending behaviour, modulus of elasticity, minimum breaking load, torsional strength, longitudinal elongation processes, flexural strength, dimensions, electrical conductivity, etc.

Contact wire wear

Wear of the contact wire is caused by mechanical friction with the contact strip of the pantograph, as well as material abrasion as a result of current transition. It is dependent on the contact wire and pantograph (contact strip) characteristics and the prevailing operating conditions. Significant factors that influence the service life of the contact wire and contact strip are the contact forces (surface pressure), step changes in elasticity, contact wire ripples, contact strip and contact wire materials, train speed, current loading and contamination. Wear is generally limited to a 20% loss in contact wire cross-section as compared to the original cross-section on high-speed railway lines, and 30% on local railway lines. Analyses of OHL systems on high-speed railway lines using copper-magnesium (CuMg) contact wires have yielded that this type of contact wire has a service life expectancy of up to 100 years (see [2]).

The causes of locally increased wear or localised greater abrasion of the contact wire will often be additional weight in the OHL system (e.g. clamps, section insulators), stronger radial forces ("corner tensions") on the steady arms or brackets (e.g. in case of smaller track radii, turnouts), excessive contact wire gradients, insufficient contact wire stagger, oscillations in the OHL system, ripples and kinks in the contact wire (e.g. manufacturing and/or installation faults). At intersecting crossovers, contact wire wear can be especially high so that, at a certain frequency of use, already after only 10-15 years of operation, a contact wire cross-section loss of 20% may be recorded.

Fine ripple of the contact wire: a phenomenon that is to be avoided

Fine ripples are deformations with small amplitudes and wavelengths in the longitudinal plane (on the sliding surface) of the contact wire. These deformations generally occur during contact wire manufacture and/or installation. If the contact wire is installed without using special equipment, then it may get bent, kinked and twisted uncontrollably – these additional generally occurring material deformations will remain even after the nominal tension force has been applied. Fine ripple causes a deterioration in the quality of current transfer between contact wire and pantograph, e.g. as a result of increased contact forces or arcing.

Clear evidence of residual fine ripple has been found particularly on contact wires made from high-strength materials (e.g. copper-magnesium (CuMg) and copper-tin (CuSn) alloys) with large cross-sections (120 mm^2 and 150 mm^2) – wavelengths of up to 1,000 mm have been observed.

In EN 50149, it is specified that, after assembly, deformations in the longitudinal plane of the contact wire (residual fine ripple) must not exceed 0.1 mm (Fig. 2).

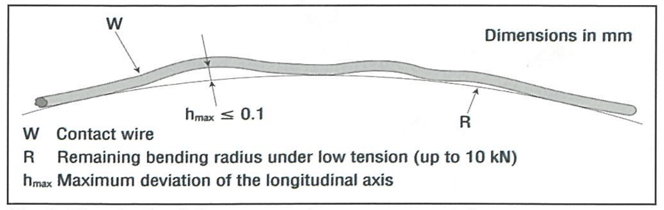


Fig. 2: Fine ripple of the contact wire must not exceed 0.1 mm(own illustration based on [3])

A study conducted in Austria has yielded that, when using the Plasser & Theurer FUM catenary installation & renewal machine technology for OHL installation (Fig. 3), which keeps the nominal tension constant in all assembly situations and installs the contact wire with the required final tension, fine ripple of the contact wire remains guaranteed within the limit of 0.1 mm defined by EN 50149, as alluded to in the following.

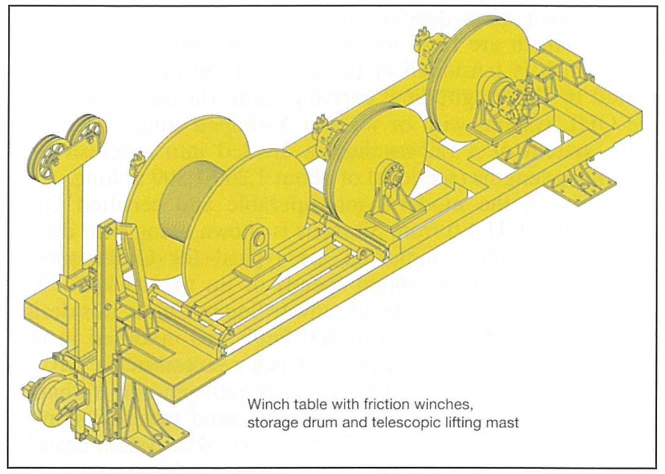


Fig. 3: Winch table of the FUM catenary installation & renewal machine (source: Plasser & Theurer)

STUDY INTO OHL INSTALLATION BY THE FUM CATENARY INSTALLATION & RENEWAL MACHINE

TU Vienna, in collaboration with ÖBB INFRA AG, has conducted a study to evaluate the quality of OHL installation achieved by the Plasser & Theurer FUM catenary installation & renewal machine. All contact wire material specifics for this study (for CuMg 0.5, 120 mm^2 and CuAg 0.1, 120 mm^2 contact wires), such as tensile strength, elongation, bending behaviour, modulus of elasticity, hardness, and plastic/elastic areas over the contact wire cross-section, etc., were investigated experimentally and analysed (Fig. 4).

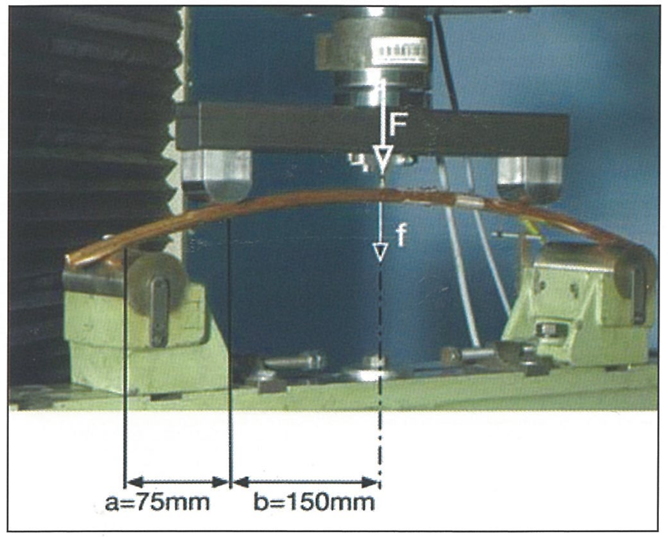


Fig. 4: Test set-up for verification of contact wire material characteristics (source [4])

In the following, the study outcome as regards fine ripple and creep is addressed.

Investigation of contact wire behaviour during installation – outcome: no residual ripple

In general, plastic bending of the contact wire already occurs when winding/unwinding it (onto/from cable storage drums, friction winch wheels, guide and deflection rollers), since the bending diameter is smaller than the calculated minimum diameter of about 3,800 mm for CuMg 0.5, 120 mm^2 contact wires. The residual plastic deformation due to small bending radii is located in the edge zones of the contact wire. For the contact wire on the storage drum, the load case "pure bending" (constant curvature, circular, no torsion) can be assumed (see also Fig. 5).

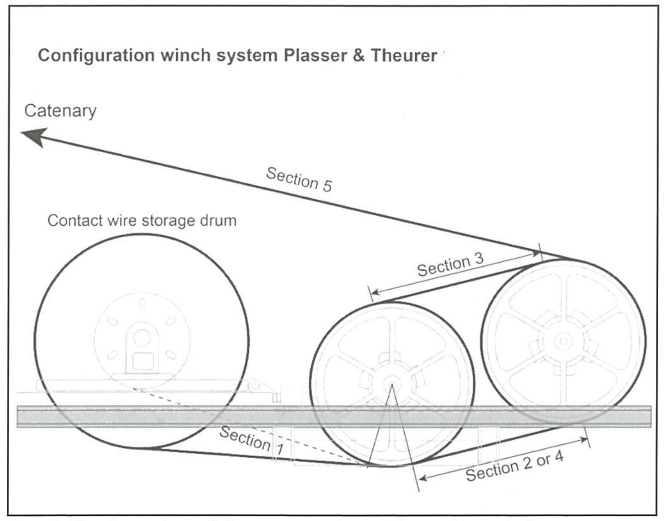


Fig. 5: Configuration of the contact wire guidance through the winch system of the FUM catenary installation & renewal machine (own illustration – source: Plasser & Theurer)

In the trial with grooved contact wire AC-120, CuMg 0.5 of type Re 330 (DB Netz AG), after a low initial contact wire tension of 8.45 kN in Section 1 of the winch system (from the storage drum), a final nominal tension of 27.0 kN was reached in Section 5 at a friction coefficient of 0.2 (Fig. 5). The residual contact wire ripple following installation was 0.05 mm – thus not exceeding the 0.1 mm defined by EN 50149!

Therefore, the outcome of this investigation is that, following installation using the FUM catenary installation & renewal machine, the contact wire does not exhibit any plastic cross-sectional areas or fine ripples.

Verification of elastic/inelastic contact wire elongation following installation – outcome: negligible creep when using the FUM technology

The longitudinal elongation of the contact wire comprises elastic elongation (elastic behaviour of the conductor material) and inelastic elongation (an irreversible, permanent change in length, also known as creep). With cables under tensile load, also a tightening of the cable basket occurs with a corresponding, permanent longitudinal elongation (depending on the stranding used and the number of layers of wire). When contact wires are installed with no or with a slight tension and, thus, "wavily", an additional permanent elongation occurs afterwards, due to "stretching" under nominal tension. Elastic and inelastic elongation (creep, stretching) of contact wires has an effect on the time needed for installation, as final assembly of the OHL components cannot be carried out immediately. This means that the railway line cannot be opened at full design speed, as this is only possible after conclusion of the elongation process – but not when using the FUM catenary installation & renewal machine technology.

Tests conducted have shown that, by using the FUM catenary installation & renewal machine, which installs the contact wire with the final nominal tension, the influence of elongation under nominal tension (inelastic, irreversible, permanent elongation, i.e. creep) on the length and position of the contact wire is negligible. This means that the cantilevers, steady arms, stitch wires, pulley tensioning units, current connectors, feeders, droppers, etc., can be installed in their final position immediately during the assembly process.

For example (see also Fig. 6), the total elongation and creep behaviour of a contact wire AC-120, CuMg 0.5 when installed with different tensile loads (Test 1 with a contact wire nominal tensile force of 27 kN, and Test 2 with a 30% increased tensile force of 35 kN) were investigated over the duration of loading. The results of the tests show that, when using the FUM, the elongation is largely completed already after about 15 minutes (900 seconds) in both cases of loading.

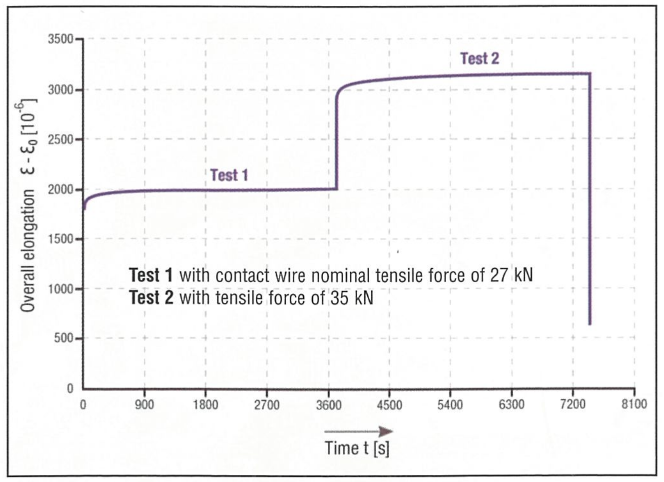


Fig. 6: Example – verification of elongation behaviour of contact wire type AC-120, CuMg 0.5 [5]

Practical application of the study results

The well-founded study results regarding the points relevant for OHL contact wire installation, such as elastic elongation under tensile force, creep behaviour, stretching, fine ripple, potential imperfections, and friction coefficients, it is possible to draw up specifications for optimum contact wire installation with supporting machine technology.

The mathematical and experimental tests that were undertaken have shown that:

- when installing the contact wire with the required final nominal tension, using the FUM catenary installation & renewal machine, no "ripple" at the contact wire occurs (thus meeting EN 50119);
- after completing one section, i.e. completion of the assembly process – when the contact wire and the carrying cable have been installed with the nominal tensional forces specified by the respective OHL design, using the FUM – the influence of elongation under nominal tension (inelastic, irreversible, permanent elongation, i.e. creep) on the length and position of the contact wire is negligible (this means that the cantilevers, steady arms, stitch wires, pulley tensioning units, current connectors, feeders, droppers, etc., can be installed in their final position during the assembly process);
- after completion of the assembly process, using the FUM, no further corrections and regulation work or adjustments to the OHL system are necessary and, thus, also no further track closures or track possessions;
- using the FUM, the assembly time is far shorter than when using "conventional assembly methods" (the latter do require adjustments to the OHL system after installation).

Thus, the technology adopted by the FUM catenary installation & renewal machine, which keeps the nominal tension constant in all assembly situations and installs the contact wire with the required final tension, is well suited for the installation of OHL systems of high-speed railway lines, where a precision of installation is of paramount importance to ensure a high quality of current transfer between contact wire and pantograph.

OHL SYSTEMS FOR HIGH-SPEED RAILWAY LINES – CONSIDERATIONS

High train speeds require a precise OHL system geometry and high-strength contact wires. As noted earlier, for contact wires made from "high-strength" materials, their production and the technology used for their installation have a significant influence on the quality of current transfer between contact wire and pantograph – there must be an uninterrupted interaction between contact wire and pantograph and, thus, a smooth current collection under all operating conditions. New calculation methods and exact measuring processes are described in the various European standards, e.g. EN 50119, EN 50317, EN 50318, EN 50367, EN 50368 and EN 15273.

OHL systems comprise contact wires, carrying cables, return cables, earth wires, feeder cables, booster lines and negative feeders, which are fixed to supporting structures. The contact wire, which is tensioned at the nominal tensile force, is supported by the longitudinal carrying cable via droppers. There are OHL systems with or without Y-shaped stitch wires. The OHL system of a railway line is divided into successive re-tensioning lengths (sections) of about 1,200-1,500 m long.

In Fig. 7, the modern, interoperable and certified OHL design SICAT H 1.0 from Siemens is shown along with design details. The values indicated are typical for OHL systems designed for train operating speeds of up to 400 km/h. For the Beijing-Tianjin high-speed railway line in China, this design for train operating speeds of 400 km/h was modified in collaboration with Chinese experts, which resulted in the SICAT HAC design, which has shorter span lengths and no Y-shaped stitch wires. Trends are noticeable that tend towards simpler, assembly-friendlier and more economical OHL system designs. OHL systems have to meet various geometric parameters, a number of which are addressed in the following.

Infrastructure clearance gauge

When implementing an OHL system, the infrastructure clearance gauge should be taken into account, such as the mechanical-kinematic clearance gauge for pantograph operation. In addition, clearance gauges for other infrastructure installations (e.g. signalling systems), as well as the installation of the OHL system itself and its associated electro-technical safety clearances must be observed. The electrical pantograph boundaries are governed by the voltage system that is used. Fundamental information on how to calculate the minimum clearance gauge for pantographs, as well as the mechanical-kinematic and electrical boundaries, are defined in EN 15273.

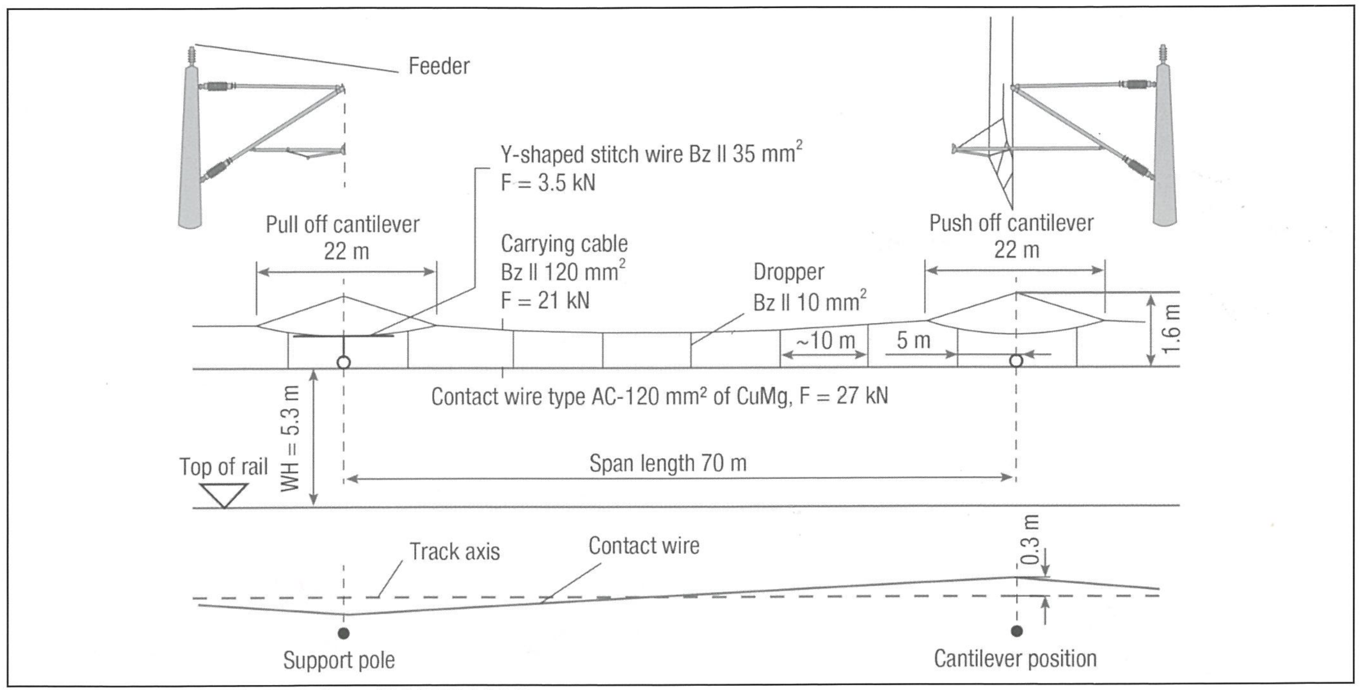


Fig. 7: Modern interoperable OHL design SICAT H 1.0 [6]

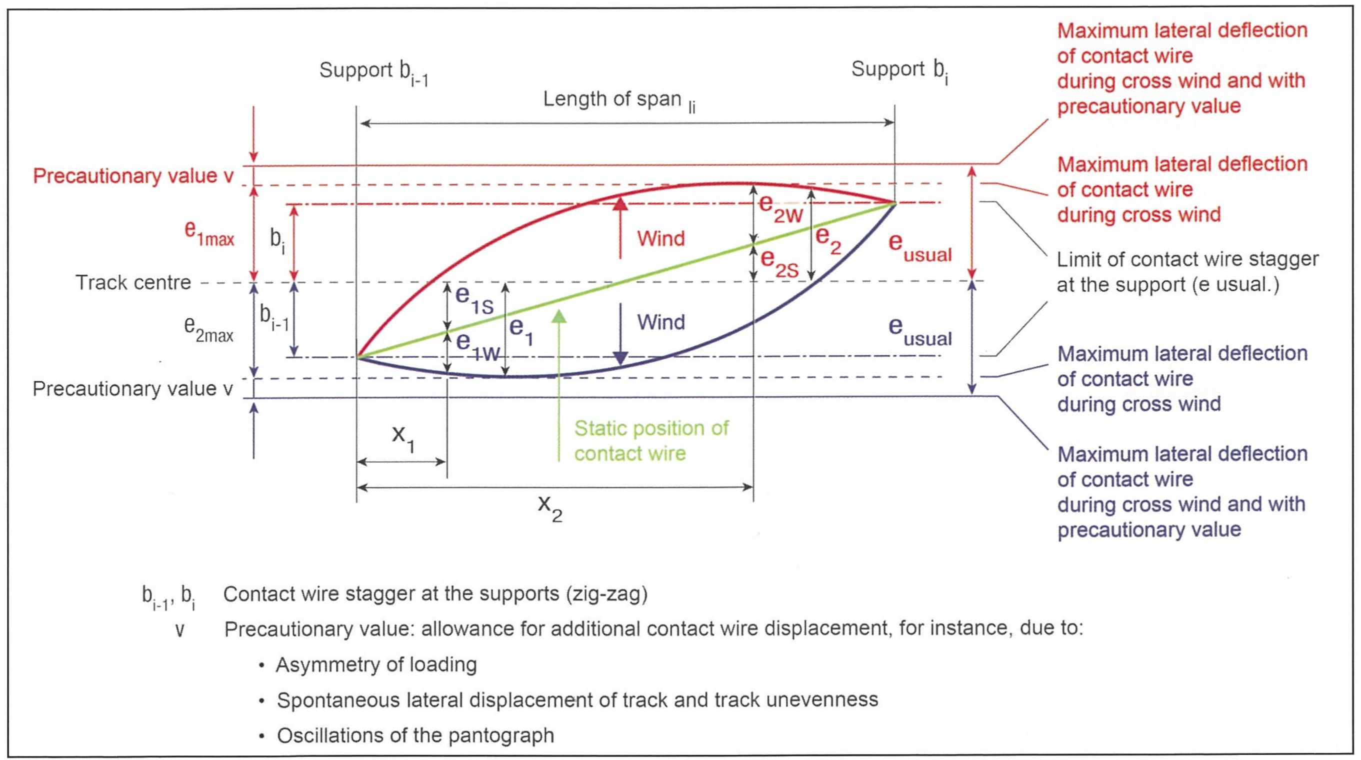
Horizontal working range of the pantograph contact strips

In all possible lateral movements of the pantograph and contact wire during operation, the horizontal working range of the pantograph head must always extend beyond the outermost static and dynamic position of the contact wire. For normal operation, the contact wire is required to move only within the usable length of the contact strip.

Under normal operating and environmental conditions, the contact wire should continually use the full length of the contact strip, in order to ensure that the latter wears down evenly. For this reason, the contact wire is staggered with an opposing lateral displacement to the track centreline and, in the case of track curves, the maximum permitted contact wire stagger can be utilised. For pantograph lengths of 1,950 mm, the usual contact wire stagger at the point of support is ±400 mm. For the interoperable pantograph length of 1,600 mm, it is currently ±300 mm.

Contact wire deflection under wind load (see also Fig. 8)

Under wind load (cross wind) conditions, both the contact wire and the carrying cable deflect horizontally. This deflection is relevant for the working range of the pantograph head. It is directly proportional to the wind force and to the square of the span length, and inversely proportional to the horizontal tensile force of the contact wire. The deflection of the contact wire is reduced by the connection to the carrying cable via the droppers (restoring forces).



b_{i-1}, b_i Contact wire stagger at the supports (zig-zag)

v Precautionary value: allowance for additional contact wire displacement, for instance, due to:

- Asymmetry of loading
- Spontaneous lateral displacement of track and track unevenness
- Oscillations of the pantograph

Fig. 8: Contact wire deflection on straight track – stagger depending on wind direction (own illustration based on [7])

To limit the wind deflection of the contact wire to the permissible values in the mid-span region, the span length must be suitably chosen (possibly shortened) and/or the contact wire nominal tensile force must be increased.

The maximum permissible horizontal deflection of the contact wire relative to the track centreline takes into account the effect of cross wind on the contact wire, as well as on the trains and pantographs. Track geometry tolerances, especially cross fall, also have a significant influence. In accordance with EN 15273, a precautionary value for the relevant influences is taken into consideration. As per EN 50367, the limit for maximum lateral deviation is 550 mm for pantograph lengths of 1,950 mm, and 400 mm for pantograph lengths of 1,600 mm.

Contact wire height and vertical working range of the pantograph

The nominal, minimum and maximum contact wire heights determine the "constructional clearance" for OHL systems and the infrastructure, as well as the working range of the pantograph. For example, EN 50119 specifies a nominal contact wire height of 5,080-5,300 mm for train operation at a speed of $V \geq 250$ km/h, and 5,000-5,750 mm for train operation at a speed of $V < 250$ km/h. In accordance with EN 50119, the vertical working range of pantographs is to be designed for a lowest and a highest working position with a working range of $\leq 2,000$ mm.

Static and dynamic criteria for OHL systems

OHL systems and pantographs must be designed and built in such a manner that, at all train speeds, as well as at standstill, a trouble-free electrical and mechanical contact between contact wire and pantograph is ensured and, thus, a high reliability and quality of current transfer. In this respect, rail infrastructure operators and authorities consider elasticity an important assessment criterion. Differences in elasticity near the supporting points of OHL systems as compared to the mid-span region decrease with higher tensile forces in the contact wire and carrying cable. These differences in elasticity can be reduced by implementing additional Y-shaped stitch wires at the supporting points.

The interrelationships, interactions, interoperability and parameters for the quality of current transfer between contact wire and pantograph are set out in TSI ENE and TSI LOC&PAS, EN 50367, EN 50119, EN 50149, EN 50317, EN 50318 and EN 50388, as well as related guidelines from rail infrastructure managers.

Contact wire uplift

The pantograph lifts the contact wire in proportion to the elasticity at a given point. For design engineering reasons, only a limited uplift of the contact wire is possible at the supporting points.

In Fig. 9, the relationship between contact wire uplift and train operating speed is shown for the new Wuhan-Guangzhou high-speed railway line in China.

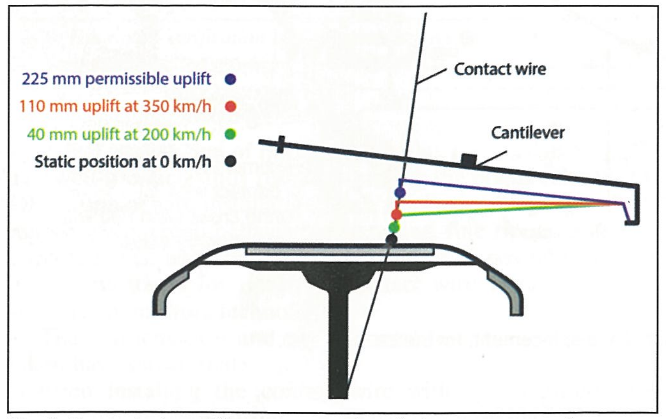


Fig. 9: Contact wire uplift at support points during test runs on the Wuhan-Guangzhou high-speed railway line in China (own illustration based on [8])

The uplift of the contact wire at low and average train speeds, i.e. up to about 50% of the wave propagation speed, is roughly proportional to the elasticity of the contact wire and to the contact force. With increasing speed, the motion-dynamic contact force increases, therefore the elasticity must be kept as low as possible to restrict the uplift. The room for free and unrestricted uplift at the supporting points must be at least double the calculated contact wire uplift as per EN 50119.

Dynamic contact wire behaviour

EN 50367 stipulates the functional requirements and technical criteria for contact wire/pantograph interaction to ensure an uninterrupted current collection. These include contact wire geometry and characteristics, pantograph characteristics, dynamic behaviour, quality criteria, permissible contact forces, operating conditions, current-carrying capacity, vehicle characteristics, etc.

The main operating conditions that need to be observed are train speed, OHL design and pantograph design, as well as the number, spacing and position of the pantographs in the train configuration.

The wave generated by contact wire uplift during pantograph passage propagates at a speed c that is dependent on the density ρ and tension σ of the contact wire:

$$c = \sqrt{\sigma / \rho} \qquad V_{max} = < 0.7 \text{ x } c$$

In line with experience gained in practice and the stipulations as per EN 50119, the train speed must not exceed 70% of the wave propagation speed c. In the case of the AC-120, CuMg 0.5 type Re 330 grooved contact wire of DB Netz AG at a tensile force of 27 kN, this results in $c = 572$ km/h and $V_{max} = 400$ km/h.

FINAL REMARKS

When implementing OHL systems for high-speed railway lines, various considerations have to be taken into account to ensure an optimised uninterrupted current transfer between contact wire and pantograph (e.g. contact wire material characteristics, wear, fine ripple, elastic/unelastic elongation, creep, infrastructure clearance gauge, working range of pantograph, contact wire deflection under wind load, static and dynamic criteria for OHL systems, contact wire uplift, as well as method of installation).

Therefore, a high-quality installation of the OHL system components is of paramount importance. The study conducted by TU Vienna in collaboration with ÖBB Infra AG has confirmed that this can be achieved by the FUM catenary installation & renewal machine, which keeps the nominal tension of the contact wire and carrying cable constant in all assembly situations and installs the contact wire with the required final tension, thus ensuring a high reliability, availability, maintainability and safety (RAMS) of the OHL system of the respective high-speed railway line.

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