Enhancing of Operational Reliability of Catenary and Electric Rolling Stock Wire Connections

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Abstract. The article deals with technological possibilities of operation reliability enhancement of high-current electrical connections while assembling unattended assembly joints under the pressure of pulsed magnetic field. The results of numerical modeling and experimental research of the catenary assembly process for the monometallic, bimetallic and composite multistranded wires between themselves and between them and terminals including those resulting vias made of aluminum and copper. The results of heat and electric tests of resulted connections are presented. It is ascertained that mechanical breaking strength of connections obtained under the pressure of pulsed magnetic field reaches 98…100% of intact wire strength. The factors of electrical contact defectiveness per resistance and per overtemp with rated current while making magnetic-impulse assembly of a wire and a coupling are lower than limit values, which are established for connections of feed wires, connectors and connecting clamps, which are obtained by pressing.

1. Introduction
Operational reliability is the property of elements or systems to perform functions preserving values of specified characteristics within the prescribed limits in the course of the time, which comply with required usage modes and use conditions. Operational reliability of rolling stock and electric system of railway catenary are defined by aggregate exposure to destabilizing factors of environment, real usage modes, maintenance and repair quality under approved design solutions and technological concepts.

Multistranded wires are used as conducting feeding, amplifying, screening and carrying cables of catenary. They may be made of copper, aluminum, steel, bimetals and composites. The choice of using materials for manufacturing wires is defined by catenary design, cross-sectional area, locations of electrified railway lines and other conditions [10]. Absent a backing-up, strict requirements are applied to reliability of connections between components of catenary, including connections in joints of carrying cables, DC line feeders and high-density sections of AC lines, as well as in subcatenary wires, the usage of which is necessary on express lines.

2. Problem statement
The By reference to working conditions and operation of catenary and electric motive power, the main problems, which should be solved to enhance operational reliability, include:

- reduction of wire and contact joint heating;
- updating of wire connecting methods, elimination of bolt clamps and fastenings on current-conducting components.

Power-transmission system operation safety, power loss reduction and saving in material resources consumption are mainly defined by reliability of electric contacts. Repetitive inspections (once in 2 years) including bolt tightening or reassembly with contact surface clearing are scheduled by operating rules of catenary. But in real-life practice of electrified railway lines operation it is impossible to carry out this due to high-intensity traffic and short duration of track possession. It is necessary to create fail-safe designs and all-metal non-assembled and unattended contact joints, providing maximal operational reliability of electric power system. Therefore the crucial task is the research dealing with multistranded wire connection methods which enable not only to enhance reliability, but to abandon inspections within wires service life [9].

In practice, contact pair copper-aluminum is widely used, e.g. in catenary storm cable connections. Creating a fail-safe non-detachable transient copper-aluminum contact joint is to a great extent connected with the development of the way of such joints production. The use of welding of these metals is rather complicated due to occurrence of intermetallides in dissimilar metals weld while heating, which cause joints fragility. Welding methods ensuring fail-safe and strong non-detachable contact are: cold pressure welding and explosion welding. While using these methods, welding is executed without external heat on account of combined plastic strain of connected metals. It is necessary to apply pressure, which excels yield tensile strength. Both of these methods require thorough preparation of connected elements surfaces, which is not always possible to provide in real-life construction conditions. In such a case, cold pressure welding all but not applicable for connecting multistranded wires, while explosion welding requires meeting demanding conditions of safety rules.

Cold pressing technology of connecting wires with welding lacks many of these disadvantages. Pressed claps are strong, lightweight, cost-effective, they do not require maintenance, they do not have declining quality of obtained current-carrying joints. They are corrosion-resistant and proof against short-circuit currents [8,11]. By pressing claps one can connect span wires, aluminum and steel reinforced aluminum wires, electrical connectors made of copper multistranded wire among themselves and with contact wires, and clump up terminals on multistranded wires of catenary and rolling stock. Wire clap assembly is carried out with split dies in predetermined sequence with pressing section lapping. When this happens unequal pressing of aluminum wire layers across its cross-section occurs. Tests demonstrate that destruction of wires constricted to a greater degree occurs in the first place. This leads to further destruction of the entire wire at comparatively low operating load.

3. Experimental

For enhancement of operational reliability of pressed claps the method of magnetic-impulse assembly of multistranded wires connection is proposed [1-4]. As opposed to pressing of couplings and terminals while pressurization by pulsed magnetic field, cylindrical part of the coupling or terminal deforms circumferentially equally, providing electric contact along all wire strands. As a result of high-speed mutual collision of connected elements and surface heating of joints by eddy currents, and their further cooling, compressive stress occurs which additionally enhances the quality of connection while carrying out the assembly.

The quality of electrical couplings is defined with factors of defectiveness of electric contact per resistance $K_R$ and overtemp by conditional rated current $K_\Theta$. Coefficient $K_R$ is defined by the relation of connection resistance to resistance of entire wire section of the same length. Coefficient $K_\Theta$ is defined by the relation of the heat flux rate in a contact joint or a branch to the heat flux rate on attachments wire

$$K_R = \frac{\Delta U_C}{\Delta U_P}, \quad K_\Theta = \frac{\Delta \Theta_C}{\Delta \Theta_P}$$
where $\Delta U_C$ and $\Delta U_P$, respectively, voltage drop in the connection and on the entire wire section of the same length, mV; $\Delta \Theta_C$ and $\Delta \Theta_P$, respectively, clap overtemp and connecting wire outside the clamp over the ambient air temperature with the same current $^\circ$C flowing in them.

While using pressed claps, factors of defectiveness of electric contact are defined by mechanical contact compaction of couplings and wires as well as wires in the connection. Therefore, for carrying out tests obstruction coefficient $K_Z$ was chosen as an optimality criterion:

$$K_Z = \frac{4S}{\pi d^2},$$

where $S$ – sum cross-sectional area of the wire and the coupling, $d$ – the outer diameter of the coupling after connection assembly.

Learning the process of magnetic-impulse assembly of electrical couplings requires research of formation process peculiarities of connections as well as defining power load optimal parameters.

Analysis of magnetic-impulse pressing of multistranded wires joints with wire sleeve, which are made of inhomogeneous materials, with the help of engineering practices, is practically impossible, because of physical and geometrical nonlinearity of the considered process. Detailed analysis of connected elements deforming process, taking into account strength characteristics of materials and their various combinations, is only possible with numerical modeling. In this research the modeling was carried out within the approach framework, which was expounded in works [5,6], and it was performed at the premises of Novosibirsk State Technical University.

In two-dimensional formulation the task of deforming wire system, which is enclosed in a coupling circular shell, is considered. Pulsed magnetic field inductor is located around the coupling. While pulse current is flowing through the inductor, eddy currents in material skin layer of the coupling are applied. When eddy currents interact with inductor magnetic field, electrodynamic forces occur, which cause mutual high-speed pressing of the coupling and the wire. Numerical modeling of the process is based on continuum mechanics equations (continuity condition, laws of mass, pulse and energy conservation, constraint equations, describing ambient behavior in the deforming process). For ambient numerical modeling the elastoplastic flux theory of Prandtl-Reiss in Lagrangian approach is used. The solution of this task is performed using numerical method, which is expounded in [6], and fulfilled in KRUNG24 program complex.

The solution of the task was performed with numerical method of finite differences. The objective of the modeling was the research of “wire-coupling” or “wire-terminal” system deforming process peculiarities under different load parameters as well as defining rational power load conditions to obtain wire claps using magnetic-impulse method. The most common types of multistranded wires were taken: 1) monometallic copper wire M-120 and aluminum wire A-185; 2), bimetallic steel-copper wire ПБСМ-95; 3) composite steel-copper wire AC-50/8. Coupling materials were: copper М1 and aluminum А0. While performing numerical modeling of assembly process of steel-copper wires ПБСМ-95, steel core and copper covering mesh areas inside all wires were revealed. While modeling the magnetic-impulse assembly process of connecting steel-aluminum wires AC-50/8, different characteristics of central wire strand material (stainless steel) and outer aluminum wires were designated. Mechanical-and-physical properties for each of above mentioned design model elements were designated.

Variable parameters in numerical modeling of assembly process for each type of connection were: charge energy of magnetic-impulse device and the coupling wall thickness. Modeling of wire connection assembly process was carried out using magnetic-impulse device MIU-30 parameters in calculations, and afterwards the device was used to perform full-scale experiments. The device’s self-inductance was $L=0,004$ uH; bank of capacitors capacitance was $C=168$ uF; maximum capacitor charge voltage was $U=19$ kV; maximum charge energy was $W=30,3$ kJ. Inductors with magnetic field concentrators for couplings with the diameter from 16 to 28 mm were used in experiments.

This allowed involving the entire frame size of selected multistranded wires. Concentrators operating space width varied from 6 to 15 mm. This allowed changing pulsed magnetic field pressure coverage and changing pressing coverage geometry.
The results of numerical modeling of magnetic-impulse assembly process of connections and the results of metallographical test of resulting connections showed that the interaction of couplings with monometallic wires М-120 and А-185 leads to uniform straining of most wire strands, their compacting and faceting (Fig. 1).

![Figure1. Cross section view М-120 and copper coupling: a) before pressing, b) after magnetic-impulse assembly](image)

In the connection of bimetallic wire ПБСМ-95 with copper coupling, steel cores of bimetallic wires practically do not undergo deformation. Severe deformation of wire strand copper cover is observed, and copper coupling material wicking into caves between strands is also observed, which additionally increases contact area of couplings and wires in a joint. While assembling the clap of steel-aluminum wire AC-50/8, faceting of outer aluminum strands occurs, whereas the central steel strand deforms insignificantly.

Minimum specific charge energy of magnetic-impulse device was chosen as assembly process efficiency criterion, which was necessary to obtain complete compacting of wire strands in connection \((K_Z \approx 1\)). Specific energy \(W_U\) for wire connection assembly was defined as the relation of magnetic-impulse device charge energy \(W\) to the volume of deformed material in the connection:

\[
W_U = \frac{W}{(F \cdot l)}, \text{ J/mm}^3,
\]

where \(F\) – coupling and wire cross-section total area in the connection, \(l\) – inductor operating space width, defining pressing zone length in obtained connection.

Under rational conditions of magnetic-impulse influence, strands deformation and final pressing of the entire wire occurs at the stage of maximum coupling (terminal) speedup with pulsed magnetic field pressure, which provides linkage of all strands and entire cross-section of connection filling in \((K_Z \approx 1\)). This can be achieved if maximum pulsed magnetic field pressure agrees with maximum coupling deformation speed. As process modeling showed coupling deformation speed in the assembly process (pressing) of connection reaches 150...200 m/s, whereas the process duration reaches 18...25 µs, depending on wall material and thickness of connecting element (coupling or terminal). If specific energy in the connection is insufficient \((K_Z < 1\)), complete strand compacting does not occur, which does not provide required quality of connection. When there is an excess of magnetic-impulse device specific energy charge, maximum coupling deformation speed does not agree with maximum
pulsed magnetic field pressure. Excess consumption of magnetic-impulse device energy charge and irrational force impact on resulting connection occur, which do not improve quality.

Metallographical tests of connection cross-sectional cuts, obtained with optimal values of magnetic-impulse device specific energy charge, confirmed the results of the process numerical modeling. Wire strands mechanical contact in the connection is observed almost over their full face. Oxides and contaminants are extruded into small-size local zones between strands. The condition of the fringes between individual strands as well as between strands and couplings in the connections mainly depends on the value of magnetic-impulse device specific energy charge and the initial gap between the outer strand layer and inner coupling surface, which defines collision speed of the coupling and the wire.

While performing magnetic-impulse assembly of vias ‘copper aluminum’ the process of forming copper wire М-120 with aluminum coupling А0 connection and forming aluminum wire А-185 with copper coupling М1 are differentiated.

The contact area of aluminum coupling with outer layer of copper strands increases significantly compared with wire А-185 connection with copper couplings. Owing to high-speed coupling and wire collision, material “wicking” of soft aluminum coupling into the space between tougher copper strands occurs. In the second case, the tougher copper coupling crushes soft aluminum strands dramatically. With that in both cases high degree of connection tightness is ensured.

4. Results and discussion

Mechanical tests of resulting connections were carried out using tensile-testing machines P-5 and P-50 with the use of cylindrical clamps for wires. As the tests showed, geometrical sizes of connecting elements significantly influence multistranded wire connection mechanical properties, where the connections were made with optimal load conditions. Strength uniformity of these entire wire connections is achieved with the coupling length of 120mm for М-120, and with the coupling length of 150mm for А-185 and ПБСМ-95. The coupling thickness for connections in all cases was estimated taking into account coupling strength uniformity with the wire.

Quality control of multistranded wire connection electric contact, obtained with pulsed magnetic field pressure, was carried out according to GOST 10434-82, GOST 17441-84 and GOST 12393-77, it was carried out indoors with the use of the heat testing facility. Joint connections of wires were tested according to specification standards as well as at cycle heating-cooling mode and at extension by rated operational load. Two special devices for connection loading while experimenting were made, which had split terminals for clamping wires of different diameters. Connection extension force was controlled according to the values of calibrated saucer spring compression, used in the device.

The number of joints was defined with factors of defectiveness of electric contact according to resistance $K_R$ and overtemp by conditional rated current $K_o$. The conditional rated current for defining $K_o$ with account for continuous current for each sort of connected wires, which is specified by regulatory technical documentation, was applied equal to 400A, 500A and 600A, and it was maintained during the testing process as unchanged to an accuracy of not more than 3% (this was controlled with multiple-purpose meter Masteh MY-62).

The overtemp value measurement of connection (coupling middle) and wire (at the distance 1 m from the coupling) was carried out with the use of thermocouples and digital multimeter APPA 109 (class 0.1). The voltage drop along the wire and in the connection was measured at each selected current value with digital multimeter Masteh M890G (class 0.1).

The factors of defectiveness with the use of copper couplings per heat and per resistance were defined for connection of wires М-120 and ПБСМ-95, whereas connection of wire А-185 with the use of aluminum couplings. For vias of wire М-120 and wire А-185 aluminum and copper couplings were used. It was ascertained that the overtemp value of resulting connections was significantly lower the overtemp value of the wires themselves outside the connection (Fig.2).
The factor of defectiveness per resistance was defined as arithmetical mean of three values, obtained with three current values. Estimation results are given in Table 1.

**Table 1.** The factors of defectiveness of joint multistranded wire connections resulting with pulsed magnetic method

| Connected wires / Coupling material | M120 + M120 | A185 + A185 | ПБСМ95 + ПБСМ95 | M120 + A185 |
|-------------------------------------|-------------|-------------|-----------------|-------------|
| KΩ                                  | 0,85        | 0,86        | 0,66            | 0,88        |
| KR                                  | 0,67        | 0,7         | 0,56            | 0,74        |

Resulting values of connection factors of defectiveness per resistance and overtemp are lower than values established for connections of feed wires, connectors and connecting clamps performed by pressing: $K_0 \leq 0.9$ $K_R \leq 1.0$ [7].

5. Conclusions

As a result of carried out research it was ascertained:

1. While using magnetic-impulse assembly of electrical connections, owing to high-speed loading condition and, as a consequence, due to impact of considerable inertial forces, deforming confinement of connected elements occurs in the pressure coverage. The coupling wall practically does not have any thinning and in contrast with connection assembly using hydraulic presses, with the use of magnetic-impulse method connection necking does not occur. Almost complete wire strand compacting in connection provides high degree of its tightness, which considerably prevents mating surfaces oxidation in operation process.

2. Magnetic-impulse assembly of multistranded wire connections is followed by partial self-clarification and mating surfaces confrication of electrical connection elements in the process of its formation. This happens due to high-speed collision and mutual deforming of a coupling and a wire. Owing to the impact of considerable frictional forces and high-speed shifting of one surface over another, intense plastic metal flow in thin boundary layers occurs. As the result of impact of considerable shearing stresses with mutual deforming and shifting of metal surface capacities of strands and connecting elements, oxides and contaminants are extruded into small-size local zones between strands. This creates tight physical contact, which provides minimum transition resistance, and this ensures long-lasting unchanged high electric contact quality in the connection.

3. Mechanical breaking strength of connections obtained by the pressure of pulsed magnetic field reaches 98...100% of intact wire strength. The factors of defectiveness of electric contact as per resistance and overtemp by conditional rated current using magnetic-impulse assembly of wire and coupling connection, are lower than values established for connections of feed wires, connectors and connecting clamps performed by pressing.
Summing up what has been said, high operational reliability of electrical connecting joints of catenary and wires of electrical rolling stock, obtained by pulsed magnetic field pressure.

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