DOI: 10.63550/ICEIP.2025.93.15.022

Influence of Ice-Wind Impacts on Rigid Lining of Open Distribution Systems

Serafim Fomenko[1][a], Igor Garanzha[2][b], Anton Tanasoglo[2][c], Milena Pisareva[2][d]
[1]*Donbas National Academy of Civil Engineering and Architecture, 86123 Makeevka, Russia*
[2]*Moscow State University of Civil Engineering (National Research University), 129337 Moscow, Russia*

Keywords: rigid busbar, busbar pipe, open switchgear, wind loads, ice loads, wind resonance.

Abstract: Ice and wind loads have a direct impact on the operation of rigid busbar structures, the degree of influence of which should be assessed qualitatively and quantitatively. Determination of design wind conditions should be based on the relevant maps of climatic zoning of the of the Russian Federation territory with specification, if necessary, of their parameters upward or downward according to regional maps and materials of long-term observations of hydrometeorological stations and meteo stations for wind speed, mass, size and type of ice and frost deposits. In poorly studied areas special surveys and observations can be organized for this purpose. The article considers an effective method of calculating the stressed state of rigid busbar structures under the action of ice-wind loads. Transverse wind oscillations caused by wind resonance can cause fatigue damage to structural elements of rigid busbar, weakening of bolted fasteners and contact connections, etc. Various methods are used to combat wind excitation. Drag coefficient up to the streamline crisis, excluding the region of small Reynolds numbers (2.5*102 ≤ Re ≤ 1.5*105), equals 1,2. In this region the flow in the boundary layer with the cylinder is laminar. In the interval 1.5*105 ≤ Re ≤ 4*105 crisis occurs: boundary layer breaks off behind the largest cross section of cylinder. In the crisis region, the circular cylinder seems to approach smoothly streamlined bodies. Behind the crisis (Re ≥ 8*105) turbulent flow is observe he drag coefficient gradually increases, reaching a value of 0.7. For a polished cylinder the coefficient c_x in this area is somewhat smaller and approximately equal to 0.5. Bus structures can be tested for strength under wind loads not only on the basis of variability coefficient. Transverse wind oscillations caused by wind resonance can cause fatigue damage to structural elements of rigid busbar, weakening of bolted fasteners and contact connections, etc. Is considered the approach of analysis for rigid busbar structures for strength under wind loads using the variability coefficient which reduces the labor intensity of engineering calculations in the design of substations opened and closed switchgear.

[a] https://orcid.org/0000-0002-1034-7409
[b] https://orcid.org/0000-0002-6687-7249
[c] https://orcid.org/0000-0002-1825-2738
[d] https://orcid.org/0009-0006-3012-2852

DOI: 10.63550/ICEIP.2025.93.15.022

1 ITRODUCTION

Problem formulation. Rigid bar (RB) (fig. 1) is designed for transmission and distribution of electrical energy between high-voltage devices in the open (open switchgear) and closed switchgear (closed switchgear) of quick-mounted complete transformer substations. One of the main issues in design of rigid busbar structure is stabilization of structure under the action of ice and wind loads (Fomenko, 2017; Dolin, 1988; Fomenko, Garanzha, Tanasoglo, Vershinin, 2019). Rigid busbars can be used together with flexible busbars, for example, in the form of a combination of rigid busbars with flexible intra-cell connections. However, the design of flexible busbars has a number of advantages over the flexible version (Fomenko, 2017; Fomenko, Garanzha, Tanasoglo, 2023; Garanzha, Tanasoglo, Fomenko, 2020; Holmes, 2022):

– use of rigid busbar allows to reduce land allocation for construction of switchgears, reduce consumption of construction materials, reduce the volume of construction and installation works;

– rigid busbar system eliminates the need for gantry structures and reduces the distance between busbars;

– time savings are achieved by reducing the number of foundations and using highly factory-ready busbars;

– rigid busbars are installed at a lower height than flexible busbars.

Based on the above advantages, it becomes clear that it is relevant to use rigid busbars at modern electric power distribution substations and, accordingly, to study the parameters of the stress-strain state of such design solutions under the influence of various types of loads under operating conditions (Fomenko, 2017; Dolin, 1988; Kuznetsov, 2019; Belostockij, Akimov, Afanas'eva, 2017).

Analysis of recent studies, publications and international stardards. The rigid busbar of open switchgear is exposed to ice and wind loads (Lozinskij, 2013; Karakozova, Mondrus, 2020; Gorokhov, Kazakevich, Shapovalov, 2000). In design practice design parameters of atmospheric effects are determined according to data of climatic zoning presented in the Regulations for Electrical Installations, and also in Code of Regulations 20.13330.2016. Load and Impacts. with specification based on regional maps and materials of long-term observations of hydrometeorological stations and meteorological posts. More detailed information on this topic can be found in (Lozinskij, 2013; Karakozova, Mondrus, 2020; Gorokhov, Kazakevich, Shapovalov, 2000), as well as in international power grid standards.

Research goal is to analyze effect of wind and other mechanical loads on rigid bus bar of open switchgear.

Research object are circular pipe structures of rigid round pipes for open switchgears of electrical substations.

Research subject are parameters of the stress state of the steel pipe-bus.

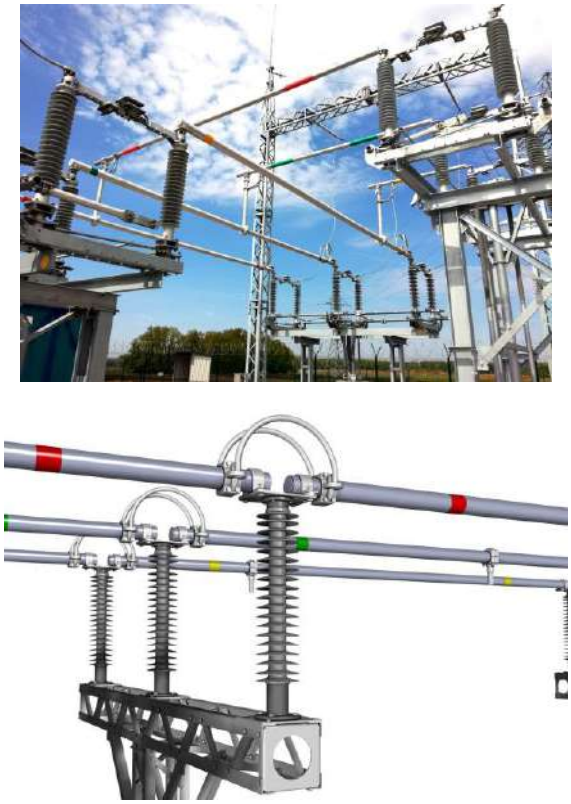

Figure 1: General view of a rigid round pipe harness.

2 MATERIALS AND METHODS

Ice loads. This type of loads are determined by normative values identified based on the cylindrical shape of sediments with density of 0,9 g/cm^3. Table 1 shows the normative thickness of ice wall zoned on territory of the Russian Federation reduced to a height of 10 m from the ground and to diameter of lightning protection cable (current-carrying wire) 10

DOI: 10.63550/ICEIP.2025.93.15.022

mm (Fomenko, 2017). At recurrence once in 25 years, in I - IV regions on ice, as well as with any recurrence in special areas, the thickness of section is recommended to be taken on basis of data processing of actual observations. In this case the calculated thickness of ice wall (for the recurrence of once in 25 years) should be not less than 10 mm (Fomenko, 2017; Fomenko, Garanzha, Tanasoglo, 2023; Garanzha, Tanasoglo, Fomenko, 2020).

Table 1: Normative ice wall thickness.

Ice district	Normative ice wall thickness, mm
I	10
II	15
III	20
IV	25
V	30
VI	35
VII	40
Special	Above 40

According to (Dolin, 1988; Fomenko, Garanzha, Tanasoglo, Vershinin, 2019; Fomenko, Garanzha, Tanasoglo, 2023) for flexible elements of the overhead line system and switchgears, namely lightning protection cables and current carrying wires, depending on the height, a correction factor for the ice wall thickness is introduced, but the height of the rigid busbar is usually not more than 25 m, which allows the correction factor to be equal to one.

The normative thickness values used in calculation of cables can be approximated for tubular buss as well.

Weight of ice deposits per unit length of bus, kg/m by (1):

$$M_i \approx \pi\gamma_1\left(\delta_1^2 + d\delta_1\right) \quad (1),$$

where γ_1 – ice density (normative), taken as follows 880 kg/m^3;

$\delta_1 = k\delta_{1n}$ – ice wall thickness (design), m;

d – bus diameter, m.

The level of normal stresses in body of busbar structure, MPa, and loads on insulators, kN, resulting from the total impact of ice weight deposits and busbar, are defined as follows (2) – (3):

$$\sigma_c = \frac{q_w l^2}{\lambda W} = \frac{g\left(M + M_i\right)l^2}{\lambda W} \quad (2),$$

$$R_i = \beta q_w l = \beta g\left(M + M_i\right)l \quad (3),$$

where g – free fall acceleration, m/s^2;

M – weight of 1 linear meter of bus length.

Strength design of rigid busbars usually includes determination of normal stresses in busbars and forces acting on the insulating part of structure (insulators) under the design combination of external loads, which, for example, can take into account loads from electrodynamic effects and ice, as well as simultaneous effect of wind and ice, etc. Resulting normal stress in a circular busbar (pipe) under the action of loads directed in mutually perpendicular planes (horizontal *xoz* and vertical *yoz* (fig. 2) is defined by formula (4):

$$\sigma_\Sigma = \frac{\sqrt{M_x^2 + M_y^2}}{W} = \sqrt{\sigma_x^2 + \sigma_y^2} \quad (4),$$

where M_x и M_y – bending moments in the corresponding planes *xoz* and *yoz*; σ_x и σ_y – bus bending stresses in the corresponding planes.

Thus, the normal stresses in rigid busbar, taking into account ice and its own weight, e.g. in case of short circuit are determined by equation (4), in which σ_x - stress caused by the action of electrodynamic loads, a - stress from the weight of rigid busbar and ice.

When external forces act in two perpendicular planes, the resulting loads on the insulators are as follows (5):

$$R_\Sigma = \sqrt{R_x^2 + R_y^2} \quad (5),$$

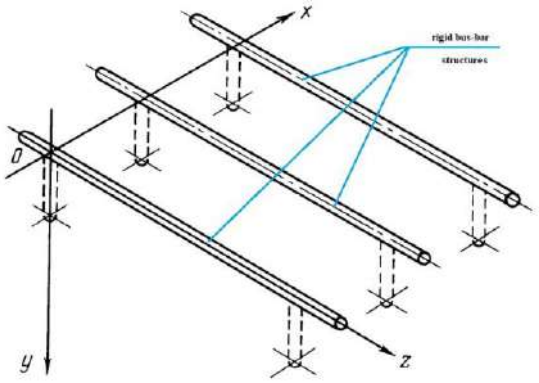

Figure 2: Coordinate system for calculating the width structure for wind and ice loads.

Wind loads. Determination of design wind conditions should be made on basis of appropriate maps of climatic zoning of territory of the Russian Federation with specification, if necessary, of their parameters upward or downward on basis of regional maps and materials of long-term

DOI: 10.63550/ICEIP.2025.93.15.022

observations of hydrometeorological stations and meteoposts for wind speed, mass, size and type of ice and frost deposits (Fomenko, Garanzha, Tanasoglo, Vershinin, 2019; Fomenko, Garanzha, Tanasoglo, 2023; Garanzha, Tanasoglo, Fomenko, 2020; Kuznetsov, 2019). In poorly studied areas, special surveys and observations can be organized for this purpose.

In the absence of regional maps, the values of climatic parameters are specified by processing the relevant long-term observation data in accordance with methodological guidelines (MU) for calculating climatic loads on overhead power lines and constructing regional maps with a repeatability of once every 25 years.

The basis for zoning by wind pressure are the values of maximum wind speeds with a 10-minute interval of averaging the speeds at a height of 10 m with a repeatability of once in 25 years (Fomenko, 2017; Fomenko, Garanzha, Tanasoglo, Vershinin, 2019; Fomenko, Garanzha, Tanasoglo, 2023).

The average wind speed varies significantly as a function of altitude. For the lower layers of atmosphere this dependence agrees well with the equation (Dolin, 1988; Fomenko, Garanzha, Tanasoglo, Vershinin, 2019; Fomenko, Garanzha, Tanasoglo, 2023) by (6):

$$\overline{V} = \overline{V}_{\phi} \frac{\ln z/z_0}{\ln z_{\phi}/z_0} \quad (6),$$

where $\overline{V}_{\phi}$ – average fixed wind speed at altitude z_{ϕ} (for example, 10 м);

z – ground elevation;

z_0 – roughness parameter.

The roughness parameter depends on the condition of the underlying surface (vegetation cover, soil conditions, snow, etc.). Average value of the roughness parameter (usually accepted in engineering calculations) z_0 = 0.2m (Dolin, 1988; Fomenko, Garanzha, Tanasoglo, Vershinin, 2019; Fomenko, Garanzha, Tanasoglo, 2023).

In most cases, the wind effect on the rigid busbar structure can be estimated by performing a static load calculation at the standard speed perpendicular to the busbar axis. In this case, the value of the static (average) wind load, N/m, acting on a unit of busbar length:

$$q = \frac{1}{2} \rho_{aer} c_x d V^2 \quad (7),$$

where ρ_{aer} – air density, kg/m^3;

c_X – drag coefficient;

d – bus diameter, м.

The density of air can be taken from reference materials or approximated by the formula (8):

$$\rho_{aer} = \rho_{aer,atm} \frac{p_{aer}}{760} \cdot \frac{273+15}{273+V_{aer}} \quad (8),$$

where $\rho_{aer,atm}$ = 1,23 kg/m^3 – air density at standard atmosphere ($p_{aer,atm} = 760\,mmHg$, $V_{aer,atm} = 15^{\circ}$C).

The values of the drag coefficient of infinitely long smooth circular cylinders of medium roughness are usually determined from the standard curve shown in Fig. 3, depending on Reynolds number $\mathrm{Re} = Vd/\nu$ (ν – air kinetic viscosity).

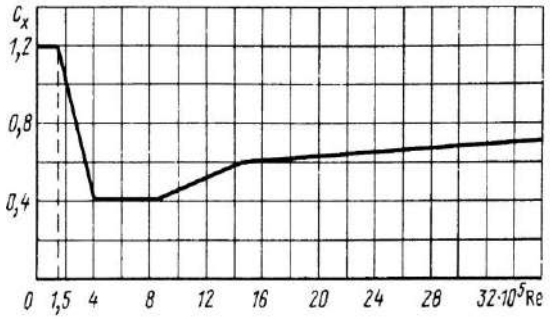

Figure 3: Normative drag coefficient of circular cylinder.

The drag coefficient up to streamline crisis, excluding the region of small Reynolds numbers (i.e. $2.5*10^2 \le \mathrm{Re} \le 1.5*10^5$), is taken equal to 1.2. In this region the flow in boundary layer with cylinder is laminar. In the interval $1.5*10^5 \le \mathrm{Re} \le 4*10^5$ crisis occurs: the boundary layer breaks off behind the largest cross section of the cylinder. In the crisis region, the circular cylinder seems to approach smoothly streamlined bodies. Behind the crisis ($\mathrm{Re} \ge 8*10^5$) turbulent flow is observed. The drag coefficient gradually increases, reaching the value of 0,7. For a polished cylinder the coefficient c_X in this area is somewhat smaller and approximately equal to 0,5.

The following formulas are used to determine the normal stresses in the material of the rigid busbar and the loads on the insulators under static forces (8):

$$\sigma_w = \frac{q_w l^2}{\lambda W}, \qquad R_w = \beta q_w l \quad (8).$$

However, the calculation of rigid busbar structures for static wind loads does not take into account dynamic nature of wind impact.

DOI: 10.63550/ICEIP.2025.93.15.022

3 RESUTS AND DISCUSSION

Dynamic effect of wind load on rigid buckling structure. The movement of air particles in the atmosphere is always turbulent, which means that the wind velocity is *V* can be interpreted as the sum of average (static) and ripple (variable) $v(t)$ constituents (9):

$$V(t) = V + v(t) \quad (9).$$

The wind ripple effect is provoked by the process of air particles braking against the earth's surface, convection between air layers with different heating temperatures, and friction between air layers moving at different speeds. The velocity pulsations are not uniform. In addition, over a time interval large enough in comparison with the prevailing period of pulsations, the statistical properties of the variable component of wind speed can be considered constant, which allows wind speed as well as wind load to be treated as stationary random processes. Taking into account a sufficiently large scale of wind turbulence, its speed along the front (within the span of the rigid frame) can be assumed to be the same and, therefore, the wind load can be considered as a stationary random function of only one time variable.

When assessing the strength of rigid busbar structures, the largest design normal stresses and loads on insulators can be represented as the sum of static and dynamic components (10):

$$\begin{aligned} \sigma_{des} &= \bar{\sigma} + \sigma^{dyn}, \\ R_{des} &= \bar{R} + R^{dyn}. \end{aligned} \quad (10).$$

Static components are mathematical expectations of stresses and loads, dynamic components are defined by standards (dispersions) of random functions σ и R, as well as the required reliability of the structures. Dynamic components can be represented as (11):

$$\begin{aligned} \sigma^{dyn} &= \gamma_\sigma \sqrt{D_\sigma} = \gamma_\sigma \bar{\sigma} V_{\text{mod}} \\ R^{dyn} &= \gamma_R \sqrt{D_R} = \gamma_R \bar{R} V_{\text{mod}} \end{aligned} \quad (11).$$

where γ_σ и γ_R – some numerical factors indirectly related to the reliability of busbars and insulators, V_{mod} – is the coefficient of variability equal to the ratio of the standard deviation to the mathematical expectation. If it is assumed that wind load ripples follow a normal distribution law, then busbar voltages and insulator loads at wind head also follow a Gaussian distribution. Then the probability of detecting stresses or loads is greater than the mathematical expectation, e.g. by one standard ($\gamma = 1$), equals 0,1587; to two standards – 0,0228; to 2,5 – 0,0062; to 3 – 0,00135 etc.

Substituting (11) into (10) we obtain (12):

$$\begin{aligned} \sigma_{des} &= \bar{\sigma}\left(1 + \gamma_\sigma V_{\text{mod}}\right) \\ R_{des} &= \bar{R}\left(1 + \gamma_R V_{\text{mod}}\right) \end{aligned} \quad (12).$$

The condition for the strength of busbars and insulators under wind effects can be written in the form (13):

$$\begin{aligned} \sigma_{des} &\le \sigma_{all} = N_\sigma \sigma_u \\ R_{des} &\le R_{all} = N_R R_u \end{aligned} \quad (13).$$

where σ_{all} и R_{all} – permissible stresses and loads; N_σ и N_R – coefficients taking into account the working conditions of rigid busbar structures, required safety margin, probability of reduction of tire tensile strength (tensile strength) σ_u and breaking loads of insulators R_u compared to normative values.

Based on design and operation experience for domestic 110 kV busbar structures, the ratio of $\left(1 + \gamma V_{изм}\right)/N$ is assumed to be 3-3,5. It is common to consider for critical structures $\gamma = 2{,}5$. In this case for 110 kV rigid busbar with logarithmic decrement of attenuation $\delta = 0{,}5$ and wind speed 25 m/s the coefficients N_R и N_σ turn out to be approximately equal to 0.6-0.7, i.e. close to the values accepted in calculations for electrodynamic resistance.

Therefore, in engineering calculations of rigid busbar structures for wind loads, design stresses in busbars and loads on insulators can be determined in accordance with formulas (10-13) when $\gamma_\sigma = \gamma_R = 2{,}5$.

For welded busbars, in addition to condition (11), inequality (14) must be satisfied (14):

$$\sigma_{des,weld} \le \sigma_{all,\,weld} \quad (14),$$

where $\sigma_{add,weld}$ – allowable stress in the weld area; $\sigma_{des,weld}$ – design stress in this area.

As mentioned above, equations (10-13) do not take into account wind loads on busbar supports. In many cases this does not introduce a significant error. Approximate design loads on insulator structures from wind effects on vertical supports are calculated as follows (15):

$$R \approx \bar{R} + \Delta\bar{R} \approx \left(\bar{R} + \Delta\bar{R}\right) \cdot \left(1 + \gamma V_{\text{mod}}\right) \quad (15).$$

Correction $\Delta\bar{R}$ is determined from the equality of bending moments at the base of the insulating support from the wind load distributed over its height and the concentrated force applied to the top of the support (16):

$$\Delta\bar{R} \approx \frac{\bar{q}\ H}{2} \quad (16).$$

where H - support (insulator) height, м; $\bar{q}$ – average wind load on the support, N/m, approximately equal to (17):

$$\bar{q} = \frac{1}{2}\rho_в \bar{c}_x d\, \bar{V}^2 \quad (17).$$

here $\bar{c}_x$ – insulator drag coefficient; d – characteristic dimension, which can be approximated as the arithmetic mean of the largest and smallest diameters of the insulator.

It should be noted that the calculation of tire structures for strength under wind loads can be carried out not only on the basis of the coefficient of variability. Other approaches are considered in (Holmes, 2022; Kuznetsov, 2019; Belostockij, Akimov, Afanas'eva, 2017), in particular, on the basis of the probability of exceeding a given level of stresses (deflections, loads). However, such estimates are more labor-intensive for engineering calculations.

Transverse wind oscillations caused by wind resonance can cause fatigue damage of structural elements of rigid busbar, weakening of bolted fasteners and contact connections, etc. (Kuznetsov, 2019; Belostockij, Akimov, Afanas'eva, 2017; Lozinskij, 2013). Various methods are used to combat wind excitation. More detailed information on this subject can be found in the works of (Holmes, 2022; Kuznetsov, 2019; Belostockij, Akimov, Afanas'eva, 2017).

4 CONCLUSIONS

1. The approach of calculation for rigid busbar structures for strength under wind loads with help of variability coefficient is considered, which reduces the labor intensity of engineering calculations in design of opened and closed switchgear substations.

2. In the course of conducted theoretical research an effective method of stress-state analysis for rigid busbar structures of open switchgear and closed of fast-mounted complete transformer substations under the ice and wind loads action has been obtained, which accelerates their design and installation.

3. The obtained methodology takes into account climatic zoning and variants of design of rigid busbar structures, which can be successfully applied in the construction of substations in poorly studied areas of terrain.

4. The presented methodology has been successfully used to assess the technical condition of rigid busbar structures at Donbass power electrical substations.

REFERENCES

Fomenko, S.A., 2017. PhD tesis, DNACEA, **163**.

Dolin, A.P., 1988. Energoatomizgat, **190**.

Fomenko, S., Garanzha, I., Tanasoglo, A., Vershinin, V., 2019. IOP Conf. Ser.: Mat. Sc. and Eng., V.**661 (1)**. 012053.

Fomenko, S., Garanzha, I., Tanasoglo, A., 2023. E3S Web of Conf., V.**383 (2)**. 04092.

Garanzha, I., Tanasoglo, A., Fomenko, S., 2020. AIP Conf. Proc. V.**2497 (1)**, 04265.

Holmes, J.D., 2022. CRC Press, **638**.

Yu. Qin, J. Cao, Sh. Cao, Ya. Ge, J., 2022. of Fl. and Struc., V.**113 (4)**. 103623.

Kuznetsov, S.G., 2019. Nord-Press, **366**.

Belostockij, A.M., Akimov, P.A., Afanas'eva, I.N., 2017. ASV, **720**.

Lozinskij, E.A., 2013. PhD tesis, DNACEA, **213**.

Karakozova, A.I., Mondrus, V.L., 2020. IOP Conf. Ser.: Mat. Sc. and Eng., V. **869(5)**. 052017.

Gorokhov, E.V., Kazakevich, M.I., Shapovalov, S.N., 2000. Nazim Ya.V., Nord-Press, **336**.

Regulations for Electrical Installations (chapter 2.5), VNIIE, **330** (2002).

Code of Regulations 20.13330.2016 Loads and Impacts, Minstroy, **105** (2016).

FGC UES Standard 56947007-29.240.055-2010, FGS UES, **101** (2010).

FGC UES Standard 56947007-29.240.056-2010, FGS UES,**17** (2010).

SOU 40.1-32385941-39:2011. GRIFE, **84** (2011).

FGC UES Standard 56947007-29.060.10.006-2008, **64** (2017).

RUS Bulletin 1724E-300, USDA, **764** (2001).