DOI 10.1007/s10749-020-01126-w
Power Technology and Engineering *Vol. 53, No. 5, January, 2020*

TOUCH VOLTAGE AND ELECTRICAL SAFETY WHEN MAINTAINING OVERHEAD POWER TRANSMISSION LINES

M. Sh. Misrikhanov[1] and A. O. Mirzaabdullaev[2]

Translated from *Élektricheskie Stantsii*, No. 8, August 2019, pp. 32 – 37.

The problem of electrical safety involving the assessment of hazardous factors during repair of overhead transmission lines is considered. The conditions of occurrence of induced voltages and the characteristics of the sources of transferred potential are analyzed. The boundaries of the effective protection zone of the grounding device of towers are determined, and the dependence of touch voltage on the characteristic zones of the grounding device is studied.

Keywords: overhead power transmission line; touch voltage; potential of grounding device; equipotential zone; equipotential coupling.

The labor protection rules [1] provide for measures ensuring safe maintenance and repair of overhead transmissions lines (OTL), electrical equipment of power stations and substations, and consumer electrical installations. These measures are multifaceted and intended to prevent injuries from various hazardous factors, primarily from electromagnetic field and electric current.

[1] National Research University "Moscow Power Engineering Institute," Moscow, Russia; e-mail: m.sh.misrikhanov@gmail. com
[2] JSC "Technical Inspection UES," Moscow, Russia.

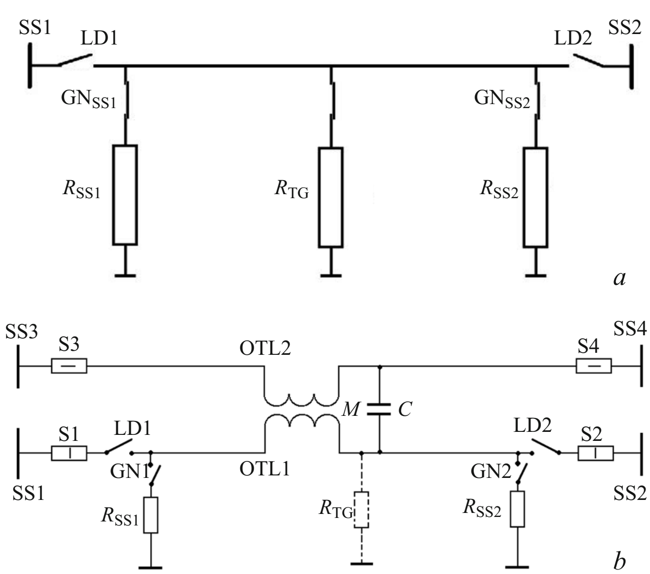

Fig. 1. Grounding of OTL according to [1]: *a*, grounding of OTL at the work location and on all sides from which voltage can be supplied; *b*, grounding of OTL.

Despite the substantial revision and restructurization of some sections, the new rules [1] follow the ideology of the previous editions [2 – 4] as regards the electrical safety in maintenance of OTLs:

(1) faulty OTL shall be disconnected and grounded at the work location and on all sides from which voltage can be supplied (Fig. 1*a*);

(2) if there is a risk of induced voltage, the faulty line shall be disconnected and grounded only at the work location (Fig. 1*b*).

This is because the rules [1] recognize only two sources of hazardous voltage at work locations of OTLs [1]:

(1) operating voltage accidentally supplied from power feeding stations or substations or break and falling of a conductor on crossed OTLs (which is considered unlikely);

(2) induced voltage when there is electromagnetic interaction between the faulty and operating OTLs and electrified railroads.

The rules [1] eliminate the risk of lightning surges by prohibiting any work on OTLs during thunderstorms.

It should be underlined that the concept of "grounding" is equally used in all editions of the rules and is based on the firmly rooted dogma that the grounding of the OTL at the work location equalizes the potentials of the conductors and the ground. Therefore, the rules [1] present the grounding of OTLs as an exhaustive technical measure that ensures electrical safety of OTL. The functional features of the grounding device [5, 6] are neglected. The rules [1] do not explicitly use the concept of “touch voltage,” although its maximum permissible magnitude of 25 V (earlier 42 V) is assumed. By “grounding” during repair of OTLs is meant protective grounding against “indirect touch voltage,” as defined in the Electric Installation Code (PUE) [7].

Before brining the new rules [1] into effect, the authors (initiators) declared in an article published in the journal Énergetik that the revision was mainly focused on induced voltage in faulty OTLs. All inaccuracies and incorrect formulations in the previous editions of the rules will be corrected and revised [8]. However, despite the restructurization of some sections concerned with the problem of induced voltage, the rules [1] do not include significant amendments that would improve the scope and safety of repair work on OTLs not only at the work location in the presence of electromagnetic influence from extraneous extended sources of voltage and current.

To formulate what is lacked in the rules [1], we will consider possible hazards disregarded by it. One is the equipotential coupling between the work location in the OTL and a point of the grid where, in case of emergency, a high potential can occur and can be transferred to grounded live and conductive elements of the OTL. There are many such points. It is expedient to divide them into two groups: (1) grounding devices of power stations and substations at which the ends of the faulty OTL are grounded, and (2) all towers of the double-circuit OTL with a noninsulated ground wire. What are these hazards?

One source occurs when the ends of the OTL are grounded in the switchgears (Fig. 1*a*), the OTL conductors are connected through the grounding blades of line disconnectors to the grounding devices (GD) of the switchgears. Therefore, the high potential induced by through short-circuit currents passing through these GDs by grounded wires is transferred to the work location.

The PUE is known to allow a high potential (5 – 10 kV) on the GDs of power stations and substations when short-circuit currents pass in them. The PUE provides for measures preventing the transfer of this potential beyond the GD by outgoing cables and other communications. To this end, their insulation is strengthened or galvanic decoupling with special matching transformers is used [7]. However, the PUE disregards the transfer of this potential by the conductors of the OTL upon disconnection and grounding through the GD of the switchgear.

Another way of transferring the hazardous potential to the work location is the non-insulated ground wire of double-circuit (multicircuit) OTLs. Earlier the PUE allowed non-insulated attachment of a ground wire only to OTLs of lower than 150 kV voltage. With the advent of optical pilot ground cables (OPGC), non-insulated attachment of ground wires is allowed for OTLs of higher voltage (up to 500 kV) [9]. If a double-circuit (multicircuit) OTL has a ground wire that is not insulated from the towers, this wire creates equipotential bonding for all the towers of the OTL. If one of the circuits is under repair with conductors grounded to the tower and an asymmetric short circuit to earth occurs in any tower of this OTL, the high potential from this faulty tower is transferred by the ground wire to a tower with temporary ground (TG) and through this TG to the faulty conductor and the work location. This potential depends on the short-circuit current and the distance between the faulty tower and the tower with TG for the faulty circuit.

Despite its short duration (0.05 – 1.0 sec), the transferred potential can reach several kilovolts, which creates at the work location a touch voltage multiply exceeding its limit established by the GOST [10].

The rules [1] address only two minimum levels of induced voltage of the five possible levels [5, 6]:

— the residual level corresponding to the classical repair circuit (Fig. 1*a*);

— the voltage drop across the GD of the tower due to electrostatic emf (Fig. 1*b*).

There remain three more levels of induced voltage that multiply exceed the levels mentioned above.

Table 1 collects reduced (to 100 km) specific induced voltages of all five levels obtained from numerous measurements and calculations. For voltages of 110 – 220 kV, the influence of the operating circuit when repairing one of the double-circuit OTLs (Fig. 2) is taken into account. For voltages of 330 kV and higher, the distance between the influencing and faulty OTLs is considered to be 50 m.

According to [1], there are only the first and third levels of induced voltage, when the OTL is grounded classically or only at the work location. Table 1 shows that it is these levels that are minimum among the ones possible for the circuit and grid configuration under consideration.

The other levels do not formally exist because have not been revealed. Therefore, they are unknown for personnel. However, if the conductor is broken in a stub or a span during repair, or if contact is lost in the grounding blades at any end of the OTL, the induced voltage can exceed the residual level by an order of magnitude and more.

The third level is observed when the OTL is grounded only at the work location. Table 1 demonstrates that this level is rather low. However, upon ungrounding of the conductor for any reason (fault of the GD to which the TG is connected, disconnection of the TG from the conductor or from the GD (tower)), the induced voltage increases by several orders of magnitude to the level of electrostatic emf.

TABLE 1. Reduced Values of Induced Voltage

Level of induced voltage	Range of induced voltage, V, influenced by OTL	
	110 – 220 kV	330 – 750 kV
Residual	10 – 100	20 – 300
Intermediate	20 – 400	20 – 400
Residual electrostatical emf	5 – 50	15 – 100
Electromagnetic emf	200 – 1000	300 – 2500
Electrostatical emf	6000 – 13,000	10,000 – 20,000

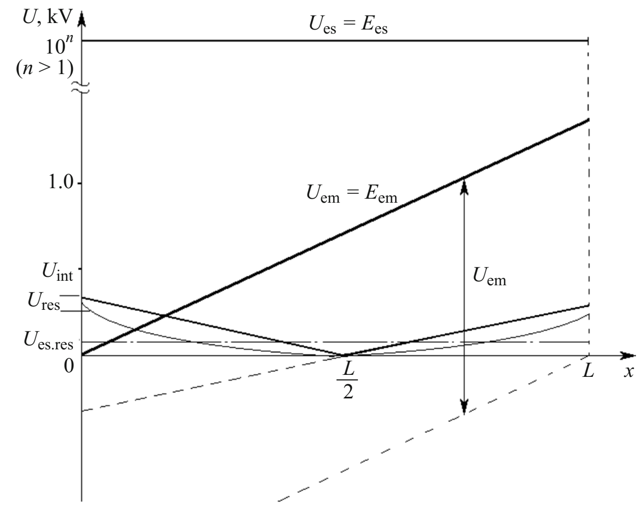

Fig. 2. Curves of variation in various levels of induced voltage: U_{es}, electrostatic emf; U_{em}, electromagnetic emf; U_{res}, residual level; U_{int}, intermediate level; $U_{\text{es.res}}$, residual electrostatic emf; L, the length of parallel run.

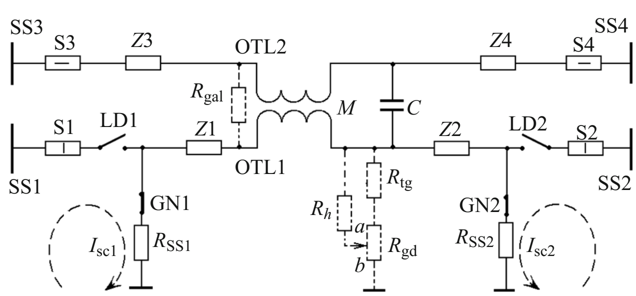

Fig. 3. Repair circuit accounting for the interaction between the faulty and operating OTLs and substations.

An analysis of injuries from induced voltage shows that they most often occur at the work location under levels of induced voltages [11] disregarded by the regulations [2, 4, 5].

Thus, to ensure electrical safety of work, it is necessary to take into account all possible hazards: erroneous (spontaneous) supply of operating voltage, induced voltage, transfer of potential from the GD of the substation and from the common ground wire. In this case, the repair circuit is shown in Fig. 3.

This circuit accounts for not only induced voltage through the inductive M and capacitive C coupling of the faulty OTL with the operating line, but also the galvanic coupling R_{gal} through the common ground wire and through the grounding blades with the GD of the substation, R_{SS1} and R_{SS2}.

To analyze the safety conditions at the work location, we will consider a fragment of the repair circuit (Fig. 3). Figure 4 details the interaction of the lineman having resistance R_{h} and grounded current-carrying elements of the OTL at the work location. When grounding the OTL by installing TG between the conductors and the metal tower, wires are con-

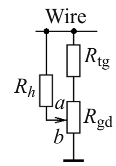

Fig. 4. Fragment of Fig. 3 for analysis of the touch voltage near the grounding device at work location.

nected through the tower to its grounding device. When TG is installed on a single-member pole, the conductors are also connected through the male-end fixtures to the GD of this pole. Therefore, depending on where the lineman is located relative to the GD of the tower, there can be different situations. If the lineman is standing on the metal tower (point a in Fig. 4), then the touch voltage is given by

$$U_{ha} = I_{\text{sc}} \frac{R_h R_{\text{tg}}}{R_h + R_{\text{tg}}}, \tag{1}$$

Since $R_{\text{h}} \gg R_{\text{tg}}$ (R_{tg} is the resistance of temporary ground), expression (1) takes the form $U_{ha} \approx I_{\text{sc}} R_{\text{tg}}$, which means that the touch voltage is within permissible limits when $R_{\text{tg}} \ll 1$.

For example, if $R_{\text{tg}} = 0.05\ \Omega$, then considering the short duration (0.1 sec) of a touch voltage of up to 500 V [10], the TG installed on the tower can protect the lineman standing on that tower against a short-circuit current of up to 10 kA.

If the lineman is standing on the ground, outside the GD, i.e., when the lower contact R_{h} approaches the point b (Fig. 4), then the touch voltage is given by

$$U_{hb} = I_{\text{sc}} \frac{R_h (R_{\text{tg}} + R_{\text{gd}})}{R_h + R_{\text{tg}} + R_{\text{gd}}}. \tag{2}$$

Unlike expression (1) where the touch voltage is determined by the resistance R_{tg} of temporary ground, in expression (2) the touch voltage does depend on R_{tg}, even if $R_{\text{tg}} = 0$.

Since $R_h \gg R_{\text{gd}}$ and $R_h \gg R_{\text{tg}}$, expression (2) yields

$$\lim_{R_h \to \infty} U_{hb} = \lim_{R_h \to \infty} I_{\text{sc}} \frac{R_h (R_{\text{tg}} + R_{\text{gd}})}{R_h + R_{\text{tg}} + R_{\text{gd}}} = I_{\text{sc}} (R_{\text{tg}} + R_{\text{gd}}),$$

and if $R_{\text{tg}} = 0$, the touch voltage is maximum $U_{hb} = I_{\text{sc}} R_{\text{gd}} = U_{\text{tr}}$, i.e., equal to the transferred potential of the tower through which short-circuit current I_{sc} flows.

Let us now consider where and how the transferred potential endangers the lineman.

The PUE considers two characteristic zones for any grounding device: current spread zone and zero potential zone ("ground") [7]. The most unstable parameter of the OTL that can greatly disturb its reliable and safe operation is the resistance of the tower GD, which depends on the resistivity of the soil and the local weather and climate conditions and ranges from several Ohms to several thousand Ohms. The higher the soil resistivity, the more difficult it is to en-

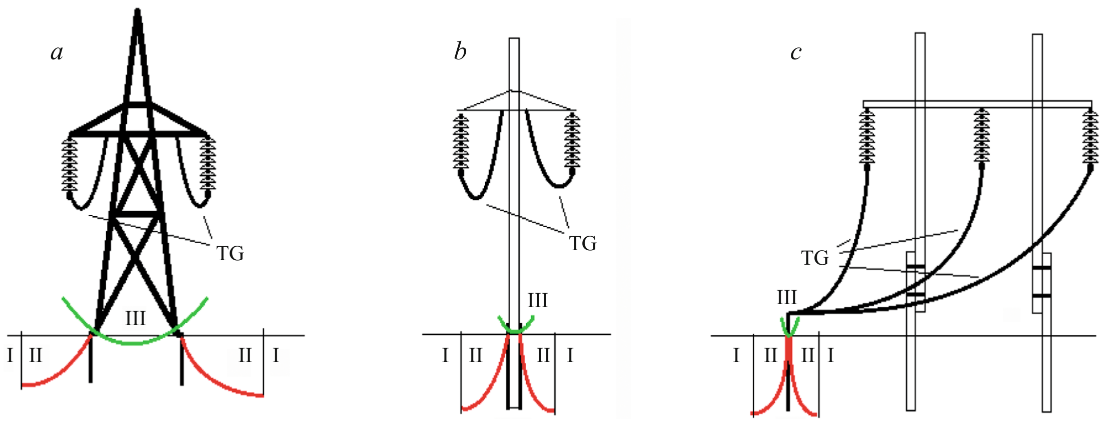

Fig. 5. Characteristic zones of GD: I, zero potential zone ("ground"); II, current spread zone; III, equipotential zone (zone of effective GD protection for different types of towers: *a*, GD of metal lattice towers; *b*, GD of single-member concrete poles; *c*, artificial GD, single post).

sure the rated resistance of the tower GD. However, the problem of electrical safety is particularly acute even for quite safe regions where the soil resistivity is below 100 Ω · m. This is because of the characteristic of the GD to which TG wires (ground wire) are grounded during repair of the OTL. Let us consider the potential characteristics for three types of GD:

— grounding of a metal lattice tower (Fig. 5*a*);

— grounding of a single-member reinforced-concrete pole (Fig. 5*b*);

— single grounding post (Fig. 5*c*).

Figure 5 shows the characteristic zones of various GDs. The red line shows the variation in the surface potential near the GD when short-circuit current flows, which characterizes the touch voltage and step voltage in the current spread zone. In this figure, the equipotential zone (zone III) is proposed in addition to the zones defined in the PUE (zero potential zone I and current spread zone II (green line)). The most important characteristic of zone III is that the touch voltage within this zone for any GD does not exceed the maximum value defined by GOST [10, 12, 13]. It is only within this zone that any GD can perform its protective functions. Temporary ground installed on such towers can protect the lineman only within this equipotential zone, i.e., if the lineman is standing on the tower. It can be seen from Fig. 5*c* that the equipotential zone of the artificial grounding device in the form of a single post is so small that the lineman cannot be in this zone. Therefore, a single post cannot be used as a protection for linemen at the work location.

To provide a fuller picture in terms of conventional concepts, it must be recognized that the inductive and capacitive coupling between the faulty OTL and extended current and voltage sources on OTL conductors (ground wires) induces direct-axis (inductive) and quadrature-axis (capacitve) emfs of commercial (or multiple) frequency. The galvanic coupling creates a risk of potential transfer to the work location in the OTL upon occurrence of short circuit in various sections of the grid. Therefore, depending on the points being considered and grounding circuits of the faulty OTL, the touch voltage (potential difference) between these points can be different. Hence, the real touch voltage at the work location depending on the grounding circuit and the points being considered is of practical importance rather than the abstract "induced voltage." Thus, the work location must not be abstract or general (such as on the tower, in the span between towers, or within 2 km on both sides of the grounding point), but rather it must be within the equipotential zone of the grounding device to which OTL conductors are grounded in preparing the workplace.

CONCLUSIONS

1. The line personnel, operating and maintenance-and-repair personnel that prepares workplaces in OTLs, personnel conducting tests and measurements on OTLs are required to study real sources of hazardous voltage at work locations such as possible sources of transferred potential and five levels of induced voltage, paying special attention to their dependence on grounding circuits of the faulty OTL, behavior, and conditions of occurrence.

2. In any conditions, including the presence of induced voltage, an OTL should be repaired following the classical procedure: ground it at the work location and on all sides from which voltage can be supplied, specifying the place and possible level of touch voltage.

3. In preparing the workplace in an OTL, the potential must be equalized so as to ensure touch voltage and step voltage at the work location within the limits established by the GOST for any short-circuit current.

4. Work permits must indicate the work location correctly: within the equipotential zone of the grounding device, or, if necessary, the equipotential zone of the GD can be expanded using metal plates or meshes to include the work location.

REFERENCES

1. *Labor Protection Rules for Operation of Electrical Installations. Revised edition* [in Russian], Éksmo, Moscow (2019).
2. *Safety Rules for Operation of 35 kV and Higher Overhead Power Transmission Lines* [in Russian], Atomizdat, Moscow (1975).
3. *Safety Rules for Operation of Electrical Installations* [in Russian], Énergoatomizdat, Moscow (1989).
4. *Interbranch Labor Protection Rules (Safety Rules) for Operation of Electrical Installations* [in Russian], NTs ÉNAS, Moscow (2001).
5. M. Sh. Misrikhanov and A. O. Mirzaabdullaev, "Problem of safety of work on disconnected overhead power transmission lines," *Élektr. Stantsii*, No. 10, 49 – 54 (2008).
6. A. L. Kulikov and A. O. Mirzaabdullaev, "Assessment of induced voltage on overhead power transmission lines," *Énergetik*, No. 8, 12 – 15 (2013).
7. *Electrical Installation Regulaitons* [in Russian], NTs ÉNAS, Moscow (2002).
8. V. P. Dikoi, S. A. Arkhipov, P. A. Alekseev, and A. V. Lishudi, "Overhead power transmission lines subject to induced voltage," *Énergetik*, No. 8, 16 – 18 (2013).
9. *Standard Instructions RD 153-34.0-48.518–98. Rules of Design, Construction, and Operation of Fiber Optic Communication Lines on 110 kV and Higher Overhead Power Transmission Lines* [in Russian], Moscow (1999).
10. *State Standard GOST 12.1.038–82. Occupational Safety Standards System (OSSS). Electrical Safety. Maximum Permissible Touch Voltages and Currents* (*amendment No. 1*) [in Russian], IPK Izd. standartov, Moscow (2001).
11. M. Sh. Misrikhanov and A. O. Mirzaabdullaev, "Analysis of the reasons for accidents and of protective measures against induced voltage on aerial electrical transmission lines," *Power Technol. Eng.*, **43**(1), 54 – 59 (2009).
12. M. Sh. Misrikhanov, V. A. Popov, N. N. Yakimchuk, and R. V. Medov, "Calculating the induced voltage on power transmission lines being repaired," *Élektr. Stantsii*, No. 2, 30 – 36 (2000).
13. M. Sh. Misrikhanov, B. A. Popov, R. V. Medov, and D. Yu. Kostyunin, "Simulation of overhead transmission lines for computing induced voltages," *Power Technol. Eng.*, **37**(1), 53 – 61 (2003).