HAZARDS AND PROTECTIVE MEASURES AT WORK ON 20 kV LINE IN CLOSE VICINITY TO PARALLEL 220 kV LINE

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ABSTRACT

In addition to the primary work hazards of the distribution line where works are performed, on the parallel lines special hazards are also present, arising from the proximity and parallelism, primarily: the risk of direct contact with live parts of high voltage transmission line and the risk of electrical induction.
In this paper the basic guidelines are given for assessing the risk of direct contact with live parts of high voltage line, described the effects of electric and magnetic field of high voltage transmission line on the induced voltage on the medium voltage line in its vicinity and given terms of evaluation and calculation aforementioned influences. Previous theoretical considerations are applied to one example of OHL 2 kV in the vicinity of OHL 2x220 kV. In addition to the assessment of risk, additional safety and security measures at work are given to prevent the risk and the negative impact of a close parallel line.
Key words*: parallel line, work hazard, safety, direct contact, induced voltage, earthing*

INTRODUCTION

One of the biggest problems in development of medium voltage overhead lines is to provide corridors and solving property and legal issues on the routes of new lines, and this problem is particularly pronounced in areas that already undergoing high-voltage transmission lines. In such situations, one of the solutions that arises is the construction of distribution line in the corridor of an existing transmission line, with the consent and in accordance with the specific conditions of the transmission system operator.
The significance of the transmission line in power system is such that the switching off may have significant impact on the power flow, stability and reliability, therefore parallel lines should be constructed so that the work on their construction and maintenance can be performed while the transmission line is energized, using conventional and additional measures of security and protection at work.
The term parallel line is not unambiguous and is interpreted or defined differently. It is common for these different interpretations that, besides having parallel routes over certain length and distance, these lines have a certain mutual influence due to inductive and capacitive coupling. The magnitude of this influence is the main criterion in determining whether the lines are considered parallel. Thus, in Croatian Regulations on the safety and health at work with electricity [1] parallel lines are defined as those lines for which the measurements indicate that the interactions of such lines causes the the induced voltages over 50 V. So, the lines that have parallel routes at the great length, but are so far apart that practically have no mutual influence, are not considered parallel lines. On the other side, even on very short lines arranged in parallel and in close proximity to high voltage power lines, the impact of electric and magnetic fields of high voltage lines can be such that makes it difficult for safe work without the application of special protective measures. Besides, when working at a height, even much lower voltages of 50 V can be dangerous because, due to the impact to workers muscles, they can cause an accident.
Besides the theoretical consideration and description of influence of high voltage lines to close, parallel lines of medium voltage distribution network, this paper analyzes the risks and safety measures at work on an example of OHL 20 kV, that is parallel to OHL 2x220 kV in length of 1,1 km and is located in its corridor, in the immediate vicinity.

WORK HAZARDS PRESENT AT OVERHEAD DISTRIBUTION LINES IN THE VICINITY OF HIGH VOLTAGE OVERHEAD LINES

Risk of direct contact with live parts of high voltage transmission lines

Direct contact is the contact of persons or animals with active live parts [1]. When it comes to active parts at medium and high voltage, contact can also be considered as such an approaching of body parts or tools to live parts that can result with a flashover.
When working in the vicinity of high voltage it is necessary to prevent accidental contact or dangerous approaching to parts of energized line. Unlike the plants where it can be achieved by insulating barriers, obstacles, blankets, etc., when working near power lines it is practically impossible, so remains only protection by keeping a safety distance.
According to Regulation [1], the area around the active parts of plant or line is divided into three zones according to the degree of risk of touching or approaching live parts, as follows:
• zone of live-line work (zone III)
• approaching zone (zone II)
• zone of free movement (zone I).
The boundary distances of zone of live-line work (DL) and approaching zone (DV) are specified in Table I, depending of line voltage, and Figure 1 shows the division of overhead line tower into zones.

Table I: Boundary distances of zone of live-line work and approaching zone

Nominal voltage (kV)	Boundary distance of zone of live-line work DL (mm)	Boundary distance of approaching zone DV (mm)
≤ 1	no touch	300
10	120	1 150
20	220	1 220
36	380	1 380
110	1 000	2 000
220	1 600	3 000
400	2 500	4 000

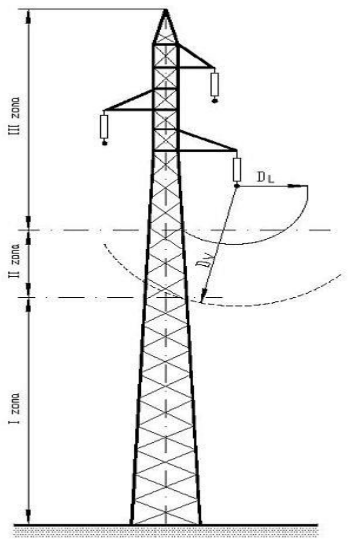

Figure 1. The division of overhead line tower into zones

Parallel lines have to be separated at least so that the work on a deenergized line can be performed without the risk of touching or approaching active parts of energized line. Since in this case is not possible to set up insulation barrier between approaching zone and zone of live-line work, the worker may be in danger even if located in the zone of approaching, because there is no reliable protection which can ensure that part of his body or non-insulated tool can not come to the zone of live-line work.
The use of construction machinery, cranes, hydraulic platforms or mounting pins, whose operating range is such, that due to reckless handling there is a possibility of intrusion in the zone of live-line work, can be particularly dangerous. It is particularly dangerous procedure of mounting poles near energized transmission line, because during the installation of pole in the prepared foundation, poles or parts of them are raised to height greater than the final height of mounted pole.

Hazards due to induced voltage

Due to electric and variable magnetic field of energized overhead power lines, voltages and currents can be induced in disconnected lines in their vicinity, such that can make difficult or disable the work or be hazardous to health or life of workers. The magnitude of induced voltage is the main criterion for the application of additional measures for protection at work on parallel lines, so it is required for any such case to make an assessment of induced voltage.

Induced voltage due to electric field (electrostatic voltage)

On disconnected and unearthed conductor located in electric field of energized line the electric charge is influenced and consequently a potential difference exist between ungrounded conductor and the earth, as well as to the active conductor that is source of electric field. These potential differences between conductors and between conductor and earth, depend on capacities between conductors and capacity between conductor and ground. In other words, the conductors of the observed line are capacitively coupled with the conductors of energized line and with the ground. In case of multi-phase and multisystem lines, the electric field is the resultant of electric fields of all conductors, so the induced voltage on disconnected line is resultant of voltages induced by electric fields of all individual phase conductors.
Figure 2 schematically shows the coupling between a conductor of disconnected line, single conductor of energized line and neutral earth. Capacity between two conductors C_{ab} (mutual capacitance) and capacity between conductor of disconnected line and earth C_{be} form a capacitive divider, so the voltage between disconnected conductor and a earth is equal to:

$$V_b = \frac{C_{ab}}{C_{ab} + C_{be}} V_a \qquad (1)$$

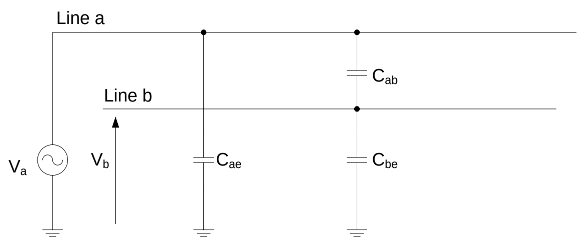

Figure 2. Capacitive coupling between the conductors of two lines mutually and with the ground

Capacity between two parallel, long conductors is function of their mutual distance and length:

$$C_{ab} = \frac{2\pi\varepsilon_0}{ln\frac{d_{ab}}{r_0}} l \qquad (2)$$

where ε_0 is permittivity of vacuum, d_{ab} is the distance between conductors a and b, r_0 is the radius of phase conductor, l is the length of the parallel conductors.

The term (3) for the capacity between the passive conductor and earth (earth capacitance) is derived from shape of the electric field between the conductor and conductive ground, which has the same shape as the field between two conductors at a distance $2h_b$, where h_b is height of disconnected, ungrounded conductor over ground:

$$C_{be} = \frac{2\pi\varepsilon_0}{ln\frac{2h_b}{r_0}} l \tag{3}$$

Since both capacities are proportional to the length, it means that the induced voltage does not depend on the length of lines, but is function of their mutual distance and height from the ground, or in other words, of the position of the conductor in the electric field created by the high voltage power line. Of course, this statement is true for very long, parallel lines, without losses, where marginal effects and other influences can be ignored. But, regardless of that, remains a fact that any conductor regardless of the length, as well as any other object, can come at a high potential to the ground if get close the high voltage conductors.

Once the disconnected conductor is earthed, voltage between conductor and earth is reduced to a negligible value, and through the earthing electrode flows capacitive current:

$$I_c = \omega C_{ab} V_a \tag{4}$$

where ω is angular frequency.

So, although the induced voltage according to (1) does not depend on the length of parallel lines, current flowing through the earthing electrode, according to (2) and (4) is proportional to the length and in case of longer parallel lines can reach life-threatening value.

Since these currents generally have low values, even in the case of relatively high earthing resistance, it can't significantly influence the earthing potential, and the potential of earthed conductor. This means that the earthing of the MV line using portable earthing device is quite sufficient to protect against induced capacitive voltages. But, it should be kept in mind that the procedure of earthing can be dangerous if ignored the correct sequence of actions in the process and therefore the worker becomes the part of the circuit between the earthed conductors and the earth.

The induced voltage due to the magnetic field

Current flowing through the conductor, in the area around the conductor creates a magnetic field. Other conductors in this field are magnetically coupled with it. For multi-phase lines, magnetic field acting on the coupled conductor is a resultant of magnetic fields of all the conductors, so the induced voltage is superposition of voltages induced by the influence of magnetic field of each conductor.

The induced voltage is proportional to the magnetic flux linkage that occurs due to the alternating current I. The term for flux linkage per length unit is:

$$\Psi = \frac{\mu_0}{2\pi} I \ln\frac{r}{r_0} \tag{5}$$

where I is the current that creates a magnetic field, r is distance from the conductor, r_0 is radius of the conductor and μ_0 is permeability of vacuum.

Since in normal operation is valid: $\sum \bar{I} = 0$ and considering the logarithmic change of flux linkage by the distance, it can be concluded that at the distances from the multi-phase line, several times larger than the mutual distances of the conductors, flux linkage will practically cancel each other, so the influence will be negligible. However, during a phase-to-earth fault in the high voltage network, when through the one of the conductors flows the current of the order of kA and more, with ground return, a strong magnetic field occurs around the conductor, what can result in dangerous induced voltage on the parallel MV line.

When one end of disconnected line is earthed, along the line is induced voltage, which value at the distance l is:

$$\overline{V_b} = \bar{I}_a \cdot \bar{Z}_{ab} \cdot l \tag{6}$$

where $\bar{Z}_{ab} = R_{ab} + j\omega L_{ab}$ is mutual impedance between the lines per length unit [Ω/m].

Once the conductor of disconnected parallel line is earthed at both ends, the current is flowing through the circuit with the ground return (Figure 3).

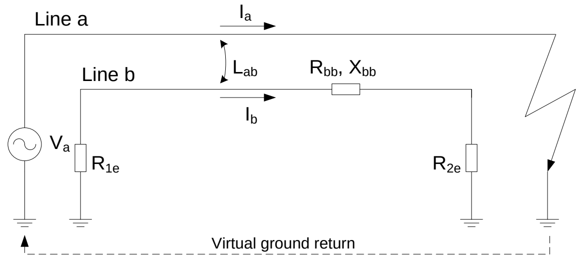

Figure 3. Current induced in a conductor earthed at both ends

Line parameters in Figure 3 can be calculated by applying Carson's terms [5], [6]:

$$L_{bb} = 2 \cdot 10^{-7} \ln\frac{D_e}{r_0} + L_u \quad \left[\frac{\mathrm{H}}{\mathrm{m}}\right] \tag{7}$$

$$R_{bb} = R_1 + R_e = R_1 + \pi^2 f \cdot 10^{-7} \quad \left[\frac{\Omega}{\mathrm{m}}\right] \tag{8}$$

$$L_{bb} = 2 \cdot 10^{-7} \ln\frac{D_e}{d_{ab}} \quad \left[\frac{\mathrm{H}}{\mathrm{m}}\right] \tag{9}$$

$$R_{ab} = \pi^2 f \cdot 10^{-7} \quad \left[\frac{\Omega}{\mathrm{m}}\right] \tag{10}$$

$$D_e = 658\sqrt{\frac{\rho}{f}} \quad [m] \tag{11}$$

where ρ is earth resistivity [Ωm], f is line voltage frequency [Hz], r_0 is radius of the conductor [m], d_{ab} is the distance between the conductors [m] and L_i is internal inductance of a conductor [H/m].
The current through the conductor of length l earthed at both ends, as shown in Figure 3 is equal to:

$$\bar{I}_b = -\frac{\bar{Z}_{ab} \cdot l}{R_{1e} + R_{2e} + \bar{Z}_{bb} \cdot l} \cdot \bar{I}_a \qquad (12)$$

where R_{1e}, R_{2e} are earthing resistances, $\bar{Z}_{ab}$ is mutual impedance between lines per length unit [Ω / m], $\bar{Z}_{bb} = R_{bb} + j\omega L_{bb}$ is self impedance of a conductor per length unit [Ω / m].
If a worker becomes the part of the circuit, his resistance is added to the earthing resistances. Since the resistance of worker is considerably higher than earthing resistances and line impedance, it will have a dominant impact to the current and in the case of short lines can significantly reduce it. However, the resulting induced current can still be lethal.

EXAMPLE OF OHL 20 KV IN THE VICINITY OF PARALLEL OHL 2X220 KV

Risk and protective measures against direct contact

The subject of analysis is the OHL 20 (10) kV for connection pole-mounted substation, parallel to transmission line 2x220 kV. The line is on wooden poles except at the ends where are reinforced concrete poles and disconnector on them. Designed horizontal distance between the axis of the lines is 10 m, and length of parallel route is 1085 m. It was determined by measurement that the minimum distance between the closest conductors of two lines is d = 7 m (Figure 4).

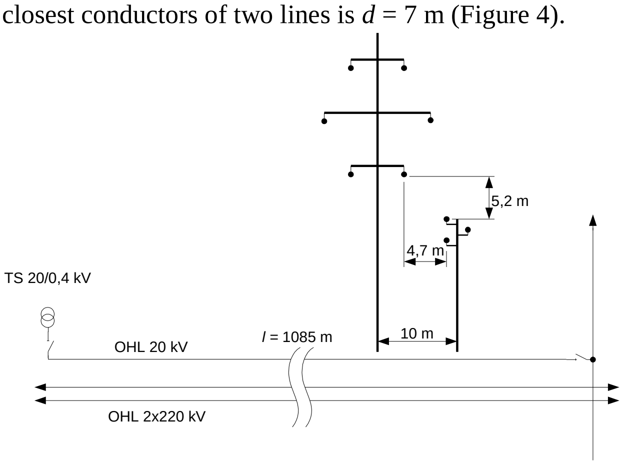

Figure 4. Position of OHL 20 kV with respect to 220 kV line

The measured minimum distance between the closest conductors of two lines d = 7 m is greater than the border distances of live-work zone and approaching zone from Table 1. Therefore it can be concluded that the work on the poles of OHL 20 kV are performing in zone of free movement of 220 kV line and with no need for additional protection measures at work as long as the worker doesn't use tools or equipment longer than 3 m, where the length of worker's hand is taken into account.
Exceptions are the works wherein high ladders, hydraulic platforms, cranes and construction machinery are used, and during installation or replacement of wooden poles and cutting plants. Such work is allowed if the distance between the workers or used equipment and the active parts of 220 kV line is longer than the safe distance DS, which for lines of nominal voltage ≥ 220 kV is 5500 mm [2]. To ensure the abovementioned safe distance of 5.5 m, when using long ladders, hydraulic platforms, cranes, construction machinery and other work equipment, application of these is permitted only on the side opposite to that at which the 220 kV line is.

Induced voltage and protective measures

For the hazard assessment, calculations of induced voltage are performed on one conductor of disconnected 20 kV line while the line 2x220 kV is energized and loaded with the rated current of 800 A. Matrices of resistance, inductance and capacity are calculated using aforementioned expressions.

Results of calculations:
1. The induced voltage on unearthed conductor: **5680 V**
2. Induced voltage at one end of the line while the other end is earthed: **13,8 V**

After the construction and before the initial operation of 20 kV line, induced voltages were measured.

Results of measurements:
1. The induced voltage on unearthed conductor: **820 V**
2. Induced voltage at one end of the line while the other end is earthed: **15,8 V** (recalculated to rated current).

Calculated and measured results show a high value of voltage induced by electric field, as opposed to the magnetically induced voltage, which has a relatively low value. However, in case of phase-to-earth fault in the 220 kV network hazardous voltage can be induced in the line earthed at only one end. Therefore, when working on this line it is recommended to apply the additional measures at work that are applied to parallel lines.
According to Regulation [1], when working on overhead lines, whose route is parallel to the route of other overhead line it is necessary to apply protective measures at work on double-circuit lines:
- overhead line where works are performing have to be earthed in places of disconnecting of power, behind disconnectors,
- line should be earthed and short-circuited on the pole where the work is performing and two adjacent poles,
- when cuting or connecting conductor, both ends of the conductor should be earthed or interconnected and earthed using the earthing and short circuiting conductor,

The greatest risk at work on this OHL appears during earthing procedure of disconnected line due to induced voltage. In the case of earthing on the first pole, there is voltage of high value on conductors of disconnected line induced due to electric field.

CONCLUSION

Works on 20 kV line can be safely performed outside the approaching zone of 2x220 kV line, respecting the safety distances and the specific requirements relating to the use of long ladders, hydraulic platforms, cranes etc. Based on the measurement and calculation results of the induced voltage on 20 kV line, the conclusion is that induced voltages on 20 kV line, due to electric and magnetic fields of 2x220 kV line, are high enough that, without application of special protective measures, can cause problems and hazard at works. Therefore, it is recommended to apply additional measures that are applied to parallel lines, which, among others, include earthing of line at both ends, on the pole where the work is performing and two adjacent poles.

Due to the demanding protective measures, that require earthing of line at five places, it is proposing to make an analysis of the real impact of the earthing at adjacent poles.

Although such placement of medium voltage lines in the corridor of the transmission line is associated with numerous difficulties, it is still feasible, with additional protective measures, especially in the case of such shorter lines.

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