SELECTION OF GROUNDING POINTS FOR LIGHTNING WIRES OF 35-750 kV OVERHEAD LINES

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For overhead lines of 35-750 kV voltage classes, the requirements for lightning shield wires, their connection to towers/pylons, and grounding are reflected in several regulatory documents. These requirements depend on many factors, including the overhead line voltage class, the presence of ice melting system and its type, the presence of optical fiber embedded into the shield wire, and the distance to switchgear. The variety of provisions scattered by different standards makes it difficult to create a complete understanding of the principles of shield wire arrangement. Let us discuss some documents and suggest a way to adjust them.

Keywords: overhead line, lightning shield wire, ground wire, OPGW, grounding of the shield wire, isolation of the shield wire, induced current, power losses.

1. INTRODUCTION

On overhead lines (OHL) of 35-750 kV classes, the main purpose of lightning shield wires (ground wires) is to protect phase wires from direct lightning discharges, which can lead to phase insulation overlap and short circuits. There are cases in the world when shield wires are installed not only on 35-750 kV OHLs, but also on 6-20 kV, however, in such cases shields wires do not serve to protect against direct lightning discharges to phase wires, but to reduce induced overvoltages on phase wires at lightning discharges close to OHLs.

As a rule, the number of shield wires on typical 35-750 kV OHL is 1 or 2. The specific number of wires depends on the OHL voltage class and the type of its towers, on the intensity of lightning activity and the requirements for the reliability of power supply to consumers.

Lightning shield wires are usually located above the phase wires, but there are cases when an additional shield wire is suspended below the phase wires – this is done to reduce the risk of back flashover from the tower body to the phase wires during lightning discharges into the main (upper) shield wires.

An additional purpose of the shield wires is to increase the protection against lightning surges of switchgear equipment. For these purposes, 1-2 shield wires must be installed and well-grounded on sections of 35-750 kV OHLs adjacent to switchgear, with a length of up to several kilometers, regardless of whether there are lightning shield wires (and how many) on the rest of the OHL. Such sections are called "protected inputs of OHL to switchgear".

Another additional functionality of the lightning shield wire on 35-750 kV OHLs can be the placement of a fiber optic in it, for the purpose of communication between switchgear located at the ends of the OHL. Such a shield wire is known as OPGW (optical ground wire).

The appearance of shield wires on OHLs requires solving many issues, including:

- selection of proper fittings for connection/suspension of the shield wire to the tower;
- selection of points along the OHL where shield wires are grounded;
- calculation of thermal stability of shield wires to lightning and short-circuit currents;
- calculation of the sufficient length of the "protected inputs of OHL to switchgear";
- arrangement of ice melting on shield wires.

Many solutions are reflected in the PUE [1] and the standards of PJSC "FGC UES", but these regulatory documents were developed either a long time ago or only by a limited group of specialists, which means that they should be openly discussed and possibly revised.

2. ANALYSIS OF REGULATORY DOCUMENTS

Requirements of [1]

The requirements to connection and grounding of shield wires are specified in [1]. According to clause 2.5.122, shield wires should be connected to towers using insulators, which are then shunted (or not) with special metal jumpers. The selection of the points of shield wire grounding depends on the OHL's voltage class, the proximity of a particular OHL's section to switchgear, the presence of ice melting or high-frequency communication.

To better understand the provisions of clause 2.5.122, let us look at them in parts.

1. "*The connection of shield wires on all towers of 220-750 kV OHLs must be carried out using insulators shunted with a spark gap of at least 40 mm. On every OHL section up to 10 km long (section between two adjacent anchor towers), shield wires must be grounded at one point by installing special jumpers on one of anchor towers.*"

This phrase means that for 220-750 kV OHLs, the shield wire should be divided into sections, each of which is grounded at one point. This solution helps avoiding of AC 50 Hz current in the shield wire induced there in normal operation mode by the magnetic field of phase wire currents (Fig.1), which means reducing the loss of power in the line. Of course, the question arises, why only for 220-750 kV OHLs, and not starting from 35 kV?

If the shield wire is divided to sections, each of which is grounded only once (Fig. 2), AC 50 Hz voltage will be induced at the end of each section, and this voltage is proportional to the length of the section and the current in phase wires. In normal operation, this voltage does not pose any danger, and in case of a short circuit, when short-circuit currents pass through the phase wires, the voltage can cause the shield wire insulator to overlap and an AC 50 Hz arc to occur there.

If the short circuit was on the OHL itself, then after disconnecting the OHL, the arc on the shield wire will go out. If the short circuit was external to the OHL, then after OHL is disconnected, the OHL will be in operation and the arc of the shield wire insulator may remain, existing due to the current that is induced in the shield wire circuit by the magnetic field of OHL's phase wires. The necessity to reduce the risk of arcing leads us to the need to limit the length of the section with single-point grounding of shield wires to 10 km only. However, for which levels of short-circuit currents is the length of 10 km specified?

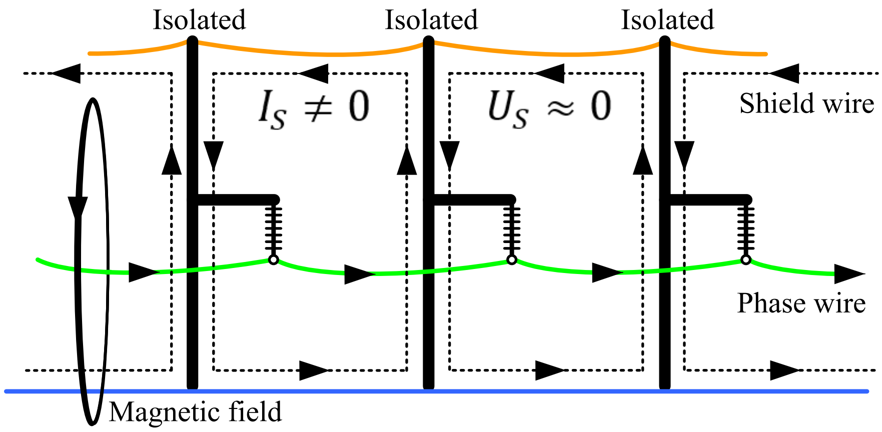

Figure 1 – Causes of current in a grounded shield wire.

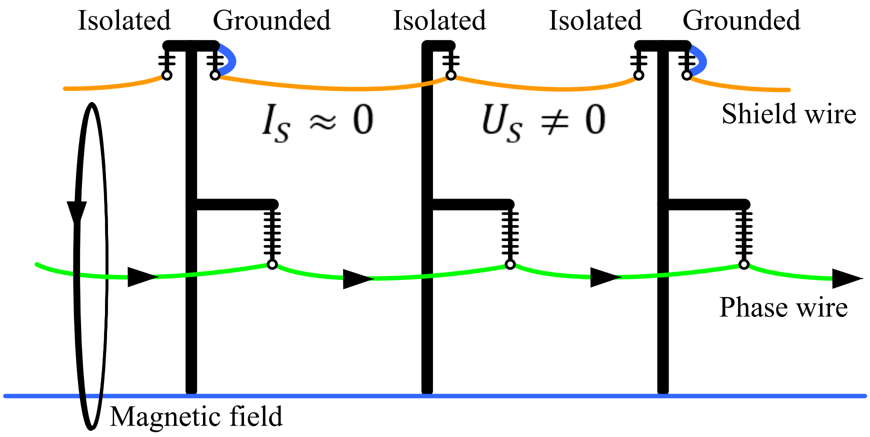

Figure 2 – An example of dividing a shield wire into sections with single-point grounding.

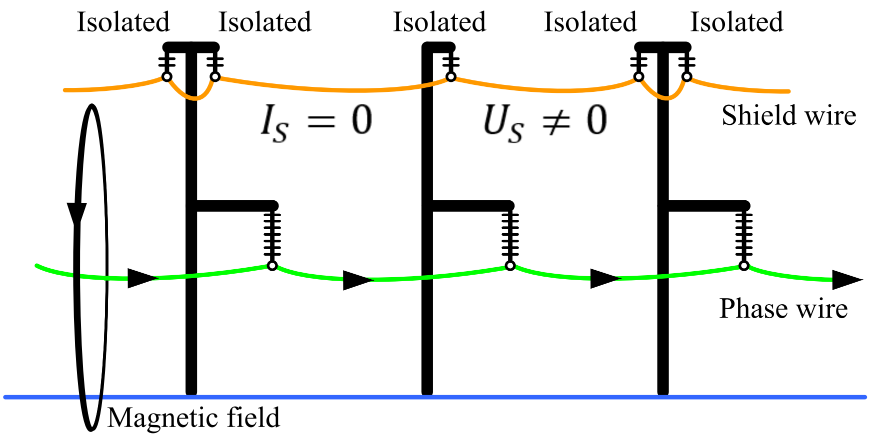

Figure 3 – An example of an isolated connection of a shield wire (common for ice melting).

In modern networks, short-circuit currents have increased compared to those in the middle of the 20th century, when PUE [1] was developed. In particular, due to the significant increase in short-circuit currents on a number of operated OHLs, it is necessary to replace shield wires with new ones, since the olds has not enough thermal stability [2].

2. "*On input sections of 220-330 kV OHLs to switchgear at a length of 1-3 km and on input sections of 500-750 kV OHLs at a length of 3-5 km, if shield wires are not used for ice melting or communication, they should be grounded on every tower.*"

The way of arrangement of lightning shield wires on OHL inputs to switchgear affects the protection of switchgear equipment insulation from lightning surges, however, a number of questions arise. First of all, why does PUE [1] only mention substations and omit electric stations? Secondly, why are only OHL's classes of 220-750 kV mentioned, and 35-150 kV are not mentioned at all – are the principles of switchgear protection for these voltage classes any different? Thirdly, as has already been shown by studies (for example, in [3]), lightning discharges to OHL at distances further than 0.5-1.5 km from the OHL input to switchgear are no longer capable of creating dangerous lightning surges inside switchgear, i.e. there is no point in arranging input sections of up to 3-5 km long.

The grounding of lightning shield wires on every tower, performed at the OHL inputs to switchgear, according to Fig.1, will mean the appearance of 50 Hz currents in shield wires. The result of current passing is not only the loss of active power in shield wires, but also the corrosion of towers and foundations, through which currents constantly flow to the ground.

We have never had to come across publications from which it would follow that the level of lightning protection of OHLs (or switchgear) in areas with shield wires grounded from one side only or without grounding at all (when melting the ice) is lower than in areas with multiple grounding. Therefore, is it so important to ground the shield wire on every tower? We are confident that on OHL's input sections to switchgear, as well as along the entire OHL route, single-point grounding of shield wires can be safely used.

3. "*On OHLs of 150 kV and below, if ice melting or the organization of high-frequency communication channels on the lightning shield wires is not provided, isolated shield wire connection should be performed only on metal and reinforced concrete anchor towers. On OHL sections with a not-isolated shield wire connection and a short-circuit current to the ground exceeding 15 kA, as well as on input sections to switchgear, shield wire grounding must be performed.*"

Firstly, it is quite difficult to interpret these provisions unambiguously. For example, is isolated shield wire connection required for all 35-150 kV OHL anchor towers (metal and reinforced concrete) or only for reinforced concrete? OHL routes are known where every tower acts as anchor tower – it turns out that on such 35-150 kV OHLs, lightning shield wire grounding is not required at all? If the isolated connection is only on the anchor towers, then does it mean that the shield wire must be grounded on all other towers?

Secondly, we repeat, it is not clear why OHLs of 35, 110, 150 kV classes, having tower design close to 220 kV, are suddenly allocated to a group separate from 220-750 kV?

4. "*When using shield wires to establish high-frequency communication channels, they are isolated from towers and grounded at switchgear and amplification points through high-frequency barriers. If ice melting is provided on OHL shield wires, then isolated connection of shield wires is performed over the entire melting area. At one point of the ice melting section, shield wires are grounded using special jumpers.*"

As one can see, in cases of communication or melting systems, PUE [1] allows not to ground the shield wire. At the same time, there is no mention in [1] of any "deterioration in the lightning protection level" of the OHL itself or switchgear, and no measures are required that would compensate for the "deterioration in the lightning protection level" of the OHL or switchgear (for example, by installing additional metal-oxide surge arresters at the inputs of OHL to switchgear, or on switchgear busbars).

In general, the lack of recommendations on the implementation of these measures is expected, since when lightning discharges to the shield wire, its isolating suspension will "instantly" be overlapped, and the shield wire will be connected to the tower, participating in the processes in the same way as it happens on OHLs with a grounded shield wire. After the impulse processes are gone, the impulse current will stop flowing at the overlap point, but 50 Hz current will remain due to the magnetic field of the phase wires. A reasonable selection of the length of the spark gaps shunting the shield wire suspension will ensure the self-extinguishing of the arc of this 50 Hz current and the transition of the shield wire to its initial state (isolated from the tower).

If, according to some provisions of PUE [1], the shield wire grounding does not affect the lightning protection of the OHL or switchgear, then the question arises again and again: for what purpose do other provisions of the PUE so persistently require a special grounding to be provided on the input sections of the OHL to switchgear, different from the rest of the OHL's route?

Requirements of [4]

Another document that addresses the shield wire connection issues is the standard [4]. Clause 4.13.1.7 of a relatively new standard [4] largely duplicates clause 2.5.190 of old [1], however, we deliberately referred to a deliberately more modern document.

According to clause 4.13.1.7, "*The design of the OPGW connection/suspension for OHLs of 110 kV and above must be carried out with the OPGW grounding on every tower. At the request of the customer (or the operating organization), the OPGW can be connected using an insulator and grounded through a shunt conductor. (jumper) It is possible to use the following scheme: in the anchor span, on one anchor tower – with OPGW grounding, on the second anchor tower and on all intermediate – with isolated OPGW suspension and connection by spark gaps; when melting ice on OHLs – with isolated OPGW suspension.*"

Firstly, here, unlike clause 2.5.122 of [1], the issues of the grounding of 110-150 kV OHL shield wires are no different from those of 220-750 kV OHLs, which, in our opinion, is completely fair. Secondly, it is important that there is no difference in the arrangement of the shield wire on the OHL and near the ends of OHL (input sections to switchgear).

Thirdly, after carefully reading clause 4.3.1.7, it seems that any option is allowed for the *OPGW*: grounding on every OHL tower, single-point grounding, and even ungrounding. At the same time, the selection of connection should be made by the Customer himself or the operating organization, based on calculations or accumulated experience – this approach, in contrast to the strict unambiguous requirements of the PUE [1], seems more rational.

3. CALCULATION EXAMPLE

As an object of research, we will select OHLs of three neighboring classes 35, 110, 220 kV, in order to additionally show that there are no reasons for allocating the issues of the grounding of shield wires of 35-150 kV OHLs to a group separate from 220-750 kV.

Let us assume that the indicated 35, 110, 220 kV OHLs are made on typical single-circuit towers with a "triangular arrangement of phase wires" such as P35-1t, PB110-1, and P220-3, respectively. We will assume that each of OHLs in normal operation has a current in phase wires equal to 500 A. We will take the shield wire type as MZ-11.0-V-OZH-N-R (at a temperature of 20°C its DC active impedance is 1.74 Ω/km).

According to calculations made in the well-known EMTP software, the 50 Hz current induced in grounded shield wire by the magnetic field of the phase wires is:

- 8.9 A for OHL 35 kV;
- 10.3 A for OHL 110 kV;
- 10.4 A for OHL 220 kV.

Assuming for 35-220 kV networks the cost of losses at the level of 0.2 eur/kWh, we obtain that for each overhead line the annual economic damage from currents in the shield wire is about 32 thousand euros per 100 km of OHL length. As we can see, classes 35, 110, 220 kV have no differences in terms of power losses in shield wires. It is unclear why the PUE [1] divided all OHLs into groups of 35-150 kV and 220-750 kV.

If, on average for the year, the current in phase wires is not 500 A, but, for example, half as much (250 A), then the current in the shield wire will also decrease by 2 times, and the annual losses in the shield wire will decrease by 4 times (to the level of 8 thousand euros per 100 km of length). Phase currents of 250 and 500 A are found both on 35-150 kV OHLs and 220-750 kV, which means that the same question arises again – why did the PUE divide the voltage classes into two different groups?

It is interesting to note that for OHLs with a horizontal arrangement of phase wires, the current in the shield wire and losses in it turn out to be noticeably higher than the values given here for OHLs with a triangular arrangement. Also, let us not forget that OHLs with horizontal arrangement usually have not one, but two shields at once, and thus the calculated losses, already increased, should also be doubled. Most often, shield wires are suspended horizontally on 330-750 kV OHLs, and if there is a need to divide OHLs into groups, then not in the same way as it was done in the PUE [1], but into 35-220 kV and 330-750 kV.

4. OPTIMAL GROUNDING OF LIGHTNING WIRE

The selection of the optimal shield wire grounding depends on many factors that need to be taken into account, but, as it seems to us, it should not depend on whether the middle part of the OHL route or its sections adjacent to switchgear are considered. In other words, the scheme should be the same throughout the entire OHL route.

For OHLs of 35-750 kV classes, there are three main shield wire arrangement types.

- Option No.1: grounding on every tower (Fig.1);
- Option No.2: division into sections grounded only from one side (Fig.2);
- Option No.3: isolated connection/suspension, that is – without any grounding (Fig.3).

Option No.1 is shown in Fig.1 and leads to the appearance of 50 Hz currents and active power losses in shield wires, the magnitude of which can be significant not only for 220-750 kV OHLs, but also for 35-150 kV. Therefore, in our opinion, it is advisable not to use this option for OHLs, regardless of the voltage class.

Option No.2 is shown in Fig.2 (in a very simplified way) – every two spans form a section grounded only at one of the ends. In practice, during OHL construction, the section usually corresponds to a section between anchor towers, and usually reaches several km.

Option No.2 is devoid of losses in shield wires and should be applied as often as possible. Although there is no current in the shield wires associated with the magnetic field of the phase wires, the shield wire is not devoid of a capacitive current associated with electric field of phase wires. Due to its small magnitude, this 50 Hz capacitive current is not capable of causing noticeable losses, but it can corrode towers and foundations by flowing down them (from the shield wire to the ground). In order to avoid such consequences, it is advisable to limit the length of each section.

Also, for option No.2, the voltage of 50 Hz in the ungrounded ends of the section is subject to verification, which is induced by currents passing through the phase wires at short circuit (in case of fault on the overhead line itself, or in the network outside the OHL). The voltage magnitude should be by a margin less than the strength of the isolating suspension of the shield wire, so as not to lead to its overlap with the subsequent occurrence of an arc, which, if the short circuit was outside the OHL, can persist for a long time.

Option No.3 should be used in those rare cases when the shield wire is either used for communications, or ice melting is arranged on it. The 50 Hz voltage appeared on the shield wire by the electric field (voltage) of the phase wires must be coordinated with the strength of the isolating suspension of the shield wire.

If we talk about the optimal way to arrange shield wires for most of 35-750 kV OHLs, then, in our opinion, it is option No.2 (Fig.2) – the one that is currently recognized by the PUE [1] for some reason only for 220-750 kV OHLs. Option No.2, in addition to the absence of losses in the shield wire, has a number of other advantages, including solving problems:

- with measuring of the grounding impedance of OHL towers;
- with thermal stability of shield wires to short-circuit currents.

Problems with measuring the grounding impedance of OHL towers appear in option No.1 with multiple shield grounding due to the fact that the grounding circuits of the towers appear to be connected in parallel to each other (due to the shield wire connecting them). To perform measurements, personnel have to climb to the top of the tower and disconnect there the shield wire, which would never have to be done in Option No.2 (Fig.2).

Problems with the thermal stability of shield wires to short-circuit currents also arise only for those OHLs where multiple grounding of shield wires is used (option No.1, Fig.1), because with short-circuit on the tower of such OHLs, the current passes not only through the tower body to the ground, but also rises up, enters the shield, significantly heating it [2]. For option No.2 (Fig.2), there will be no short-circuit current in the shield wire.

It may seem that for 35 kV OHLs, problems with the thermal stability of shield wires are not an argument to refuse from option No.1 in favor of option No.2. For example, such a position is contained in clause 4.3.1.5 of the standard [4], where it says: "*For 35 kV OHLs, due to the neutral operating mode, there is no thermal effect of short-circuit current on the OPGW, therefore calculations for the thermal effect of short-circuit currents on the shield wire are not required.*" Unfortunately, this statement is incorrect, since for a network with an isolated (compensated) neutral, a single-phase-to-ground fault provokes overvoltages on the initially unfaulty phases, which can damage their insulation, and the second ground fault occurs in the network. It means that that there will be two faulty phases at the same time (in different phases and places of the network), which means a short circuit. The current for this type of short circuit reaches $\sqrt{3}/2 = 0.87$ of the three-phase short-circuit current, i.e. it can certainly be dangerous for the shield wire of any OHL 35 kV.

5. CONCLUSIONS

1. The provisions of the PUE [1] regarding the grounding of lightning shield wires of OHL 35-750 kV need to be adjusted. In particular:

- there is no reason to separate the requirements to the arrangement of lightning shield wires for OHL 35-150 kV and OHL 220-750 kV; the requirements should be the same for all OHL 35-750 kV;
- there is no reason for differences in the arrangement of shield wires on OHL 35-750 kV between the OHL route and input sections to switchgear.

2. For all OHL 35-750 kV, the most optimal option is to divide the shield wire into sections, each of which is grounded once. The exception is when a communication channel is organized along the shield wire or ice melting is provided – in this case, a fully isolated connection of a shield wire is required, without any grounding.

3. The need to revise the PUE [1] has been discussed many times by industry experts, but the experience of recent decades suggests that the release of the next editions of the PUE is likely not to happen. Therefore, the solution to the problem is possible by preparing a new standard entirely dedicated to this topic of shield wires.

REFERENCES

1. Rules of Electrical Installations (PUE) – 7th edition. Approved by Order No.204 of the Ministry of Energy, dated 07.08.2002.
2. M. Dmitriev, S. Rodchikhin "Calculation of thermal stability of lightning shield wires of 110-750 kV overhead lines" // "Electric Power: transmission and distribution" magazine, No.3(42), 2017, pp.32-35.
3. M. Dmitriev "Lightning overvoltages in high voltage switchgear". –St. Petersburg: Publishing House of Polytechnic University, 2009. -60 p.
4. Standard STO 56947007-33.180.10.172-2014 "Technological communication. Rules for the design, construction and operation of overhead lines of 35 kV and above", 2014.