AUTOMATIC RECLOSURE FOR MIXED CABLE AND OVERHEAD LINES

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Recently, cable sections have been increasingly organized on overhead lines, which leads to the emergence of a new type of lines – mixed. As you know, automatic reclosure is very common on overhead lines, but it is useless and even harmful for cable lines. The article provides options for organizing automatic reclosure on mixed cable-overhead lines.

Keywords: cable line, overhead line, mixed line, line automatic reclosure, single-core cable, short circuit.

I. INTRODUCTION

In case of damage and short-circuit in the overhead section of the mixed line, the cycle of line automatic reclosure (LAR) is an effective way to restore power supply to consumers, but in case of damage in the cable section of the mixed line, it is not only useless, but even harmful, because it can lead to even greater damage to the cable insulation.

To study the issues of the LAR algorithms on mixed line, as follows from [1], electric grid companies even advocated conducting research work on the relevant topic.

The ideology of the LAR on mixed lines is simple: if damage is detected on the cable section, then it is necessary to ban the LAR of such a mixed line. However, as it may seem from [1], as part of the implementation of the LAR, the authors are going to solve a much more serious task – finding a specific place of the cable damage, i.e. calculating the exact distance from the line's end to the place of cable damage.

In general, the term "cable fault locating" (CFL) refers primarily to cable lines that have been put into repair. CFL on a disconnected cable line takes up to several hours, even if the work is carried out by high-class professionals with extensive experience. At the same time, appropriate preparation of the grounding circuits of the cable screens is needed, as well as a mobile laboratory equipped with a whole list of devices in which various methods of CFL are implemented, because damage can be complex, and it is not always easy to find them using any one method. Taking into account the above, there are grounds to consider to be too difficult the idea [1] to implement CFL of a mixed line automatically. Especially if we need a high accuracy within fractions of a second, which are available to make a decision on launching or abandoning the LAR.

The article shows how it would be relatively simple and reliable to organize the LAR for a mixed line without purchasing expensive and capricious CFL installations, as well as minimizing research work.

II. MIXED LINE AND ITS AUTOMATIC RECLOSURE

The concept of line automatic reclosure (LAR) is one of the basic in the electric power industry. Typically, LAR involves such a sequence of events and actions:

- damage (short-circuit) occurs on the line;
- relay protection records a decrease in voltage and an increase in current on the line;
- the protection gives the command to turn off the circuit breakers at both ends of the line;
- during "no-current pause" the damage, if it is passing, has the opportunity to disappear, that is the line insulation is going to become operable;
- an attempt is being made to supply voltage from the network to the line in order to find out whether the damage has been eliminated or not, for which a command is given at one end of the line to close the switches ("testing the line with voltage");
- if there is no damage, a command is given to close the switches at the other end of the line ("closing the line into transit"), i.e. the line returns to its original normal operation;
- if the voltage testing of the line was unsuccessful and the damage on the line insulation was not eliminated, the line is completely disconnected from the network again and requires inspection (after some time it is also possible to re-attempt testing of the line with the network voltage, and this procedure called "repeated LAR").

The concept of "mixed line" became widely used not so long ago. It is understood as:

- 110-500 kV overhead line having cable entries into switchgears, or having cable inserts along the route;
- 6-35 kV cable line placed on the overhead line towers and all its route made by so-called universal self-supporting cable (“Multi-Wiski” or “Torsada”).

Further in the article, we will consider only the first of the two listed options for a mixed cable-overhead line, since only for it we can talk about LAR.

Fig.1 shows several variants of the mixed line, which differ in the number and location of cable sections. For overhead lines the easy design of cable sections became possible after development of a single-core cables with cross-linked polyethylene (XLPE) insulation. The fact is that such cables have solid insulation, i.e. restrictions on the height difference along the route have been removed for them. Consequently, without any problems, terminations of such cables can be mounted even at a considerable height above the ground – for example, on the towers (pylons) of overhead lines. Towers with cable terminations on them are well-known so-called connection points between overhead and cable lines. The convenience of termination installation on line towers, no doubt, is due to the single-core design of cables.

The technical ability to create mixed lines is inextricably linked with the emergence of a modern generation of single-core XLPE-insulation cables, but the need for such mixed lines arises for the following reasons.

1. The switchgear is made with gas insulation (GIS), and cables have to be used to organize the entry of overhead lines into a building with a GIS.
2. A large number of overhead lines at the same time have to be connected to the same switchgear, and to save space, the connection of these lines is carried out by cables.
3. The overhead line approaches the switchgear, which is located in a region, where this line is replaced with a cable line for aesthetic reasons and because of the high land cost.
4. The passage of an overhead line through water obstacles where sometimes it’s better to put an underwater cable section instead of above water overhead crossing.

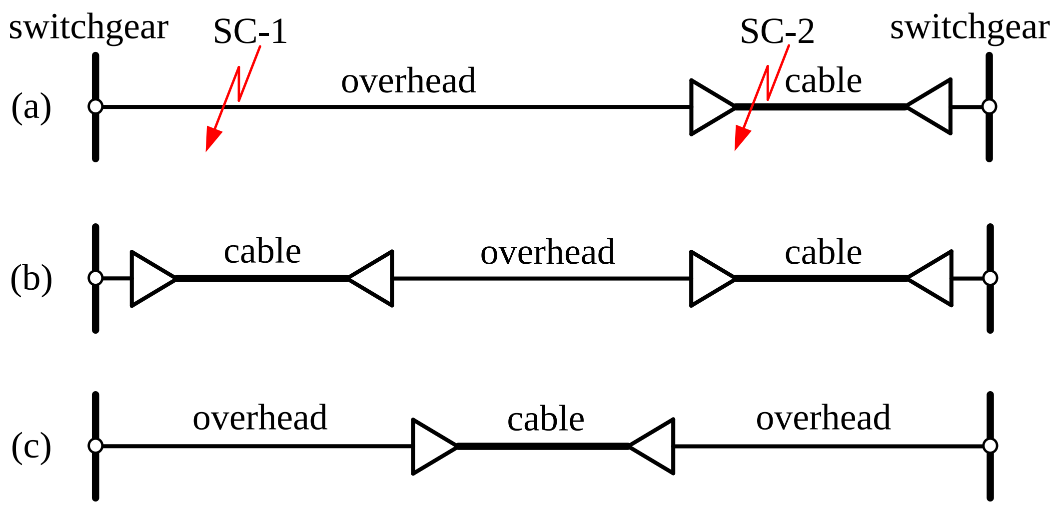

Fig.1. Different types of mixed lines and different points of short-circuits (SC):
(a) – line with cable entry into the switchgear at one end;
(b) – line with cable entry into the switchgear at both ends;
(c) – line with cable insert.

The overwhelming number of cases of the organization of cable sections on overhead lines occurs due to the reasons described in case 1 and case 2, i.e. we are talking about the cable connections of overhead lines to switchgear (Fig.1a,b). Most often, these entries have a length of no more than 500 m – it means they are performed with relatively short cables. In other words, the cable section is only a small part of the length of the entire mixed line.

Per unit length, the damage probability of the overhead section of the mixed line is noticeably higher than that of the cable section. This is because in the overhead section, the operation of the line is influenced by climatic factors (increased loads during wind and ice, insulation overlaps due to insulation humidification and lightning strikes), actions of third parties (collisions, vandalism), consequences of birds and other reasons.

So, for most mixed lines, short-circuits will occur in the overhead section, because:

– the damage rate of the unit length of the overhead section is significantly higher than the unit length of the cable section;
– the length of the overhead section, as a rule, is significantly longer than the cable section.

Considering the above, it would be an unjustified waste to introduce a ban on the LAR of a mixed line due to the presence of a cable section on it. For an overhead section LAR is a very good way to increase the reliability of consumers power supply, since the most of damages occur on the overhead section and a significant part of them are passing. Therefore, instead of completely abandoning the LAR on mixed lines, it is necessary to learn how to distinguish exactly where the damage occurred, and, if it is on the cable section, then only then give the command to ban the LAR.

After all, if you reread the above, the damage on the cable section seems to be such an exceptional event that it is not worth talking about it for the entire life of the cable. So, the question may arise – whether it is worth introducing any bans on LAR in case of damage on the cable section? In other words, why not to make the LAR unconditional, i.e. carry out LAR every time, without figuring out exactly where the mixed line damage occurred?

Yes, indeed, a short-circuit of the main insulation of the cable is a rare event, but the consequences of re-supplying voltage to the emergency cable can be extremely unpleasant:

- the repeated passage of short-circuit current through the core and screen of the damaged cable can cause overheating of the cable insulation beyond the permissible temperature and its melting not only at the site of the initial damage, but also along the entire cable route; this may require a complete replacement of the emergency cable along its entire length, which is extremely expensive;
- arc combustion products at the site of damage of single-core cable can affect and damage neighboring single-core cables (such a photo is given in the article [1]).

It is clear that it is impossible to recognize the unconditional LAR on mixed lines as good variant (it is fraught with dangerous consequences for the cables) and it is impossible to consider the full rejection of LAR as well (this is fraught with frequent disconnections of consumers). It is the prohibition of LAR in case of damage on the cable section and the permission of LAR in case of damage on the overhead section that is the only reasonable option for organizing the operation of mixed lines.

In AC networks with a voltage of 110-500 kV, two types of LAR are used on the lines – three-phase (TLAR) and single-phase (SLAR). If TLAR is used in networks of all voltage classes, then SLAR has found application primarily for lines of 330 kV and above, since for them up to 95% of damages are single-phase. Because of this, the use of a single-phase LAR allows you to save the switching resource of the switches of the undamaged line phases and at the same time to save the power transmission over the other two line phases for the time of disconnection of the damaged phase. And only if the SLAR was unsuccessful or several phases were damaged on the line at once, then an attempt is made to TLAR.

Of course, when a cable section appeared on the overhead line, it would be desirable that the algorithms of the LAR operation did not change, i.e. if the line was wound up under the SLAR, then it would be possible to save it. Since the cable sections are carried out by single-core cables, and not three-core cables, there are all the necessary prerequisites for maintaining the SLAR on the mixed line, because there is a technical possibility for phase-by-phase monitoring of the cable condition and issuing a ban on the LAR not for the entire mixed line, but only for the damaged phase.

All of the above applies to AC lines. However, DC lines have their own specifics, and the LAR can be made unconditional, i.e., the LAR can always be used without finding out whether there was damage on the overhead section or on the cable section. The fact is that DC power lines have a so-called current regulator in their composition, the action of which seriously limits the short-circuit current almost at the level of the rated current. In other words, on any mixed DC lines, short-circuits on the cable section, even when using an LAR, will not cause an accident to develop on the scale that it could be on AC lines, where the short-circuit current is several times or tens of times greater than the rated current.

In particular, on the ± 300 kV DC overhead cable line, which is planned to be built in St. Petersburg (the cable section of the line will be laid along the bottom of the Gulf of Finland), no bans on LAR should be introduced. For this line, the LAR can always be done regardless of the place of damage: simply, if the damage was on the cable section, then such a LAR is 100% likely to be unsuccessful, but it will not cause the development of the number of defects of the already damaged cable.

III. AUTOMATIC RECLOSURE AND CABLE SCREENS SCHEME

Single-core cables with XLPE-insulation, which are widely used for all AC-networks, and, in particular, on 110-500 kV mixed lines, have copper screens in their design, requiring special attention to the choice of screen bonding and grounding schemes [2].

Fig.2 shows three basic schemes for single-core cable screens bonding and grounding, differing in the values of the AC voltages and currents induced in the screens at an industrial frequency of 50 Hz, as well as the losses of active power caused by induced currents. Some of the schemes require the use of special metal-oxide surge arresters (MOA), placed either inside grounding boxes (GB-MOA), or inside cross-bonding boxes (CBB-MOA).

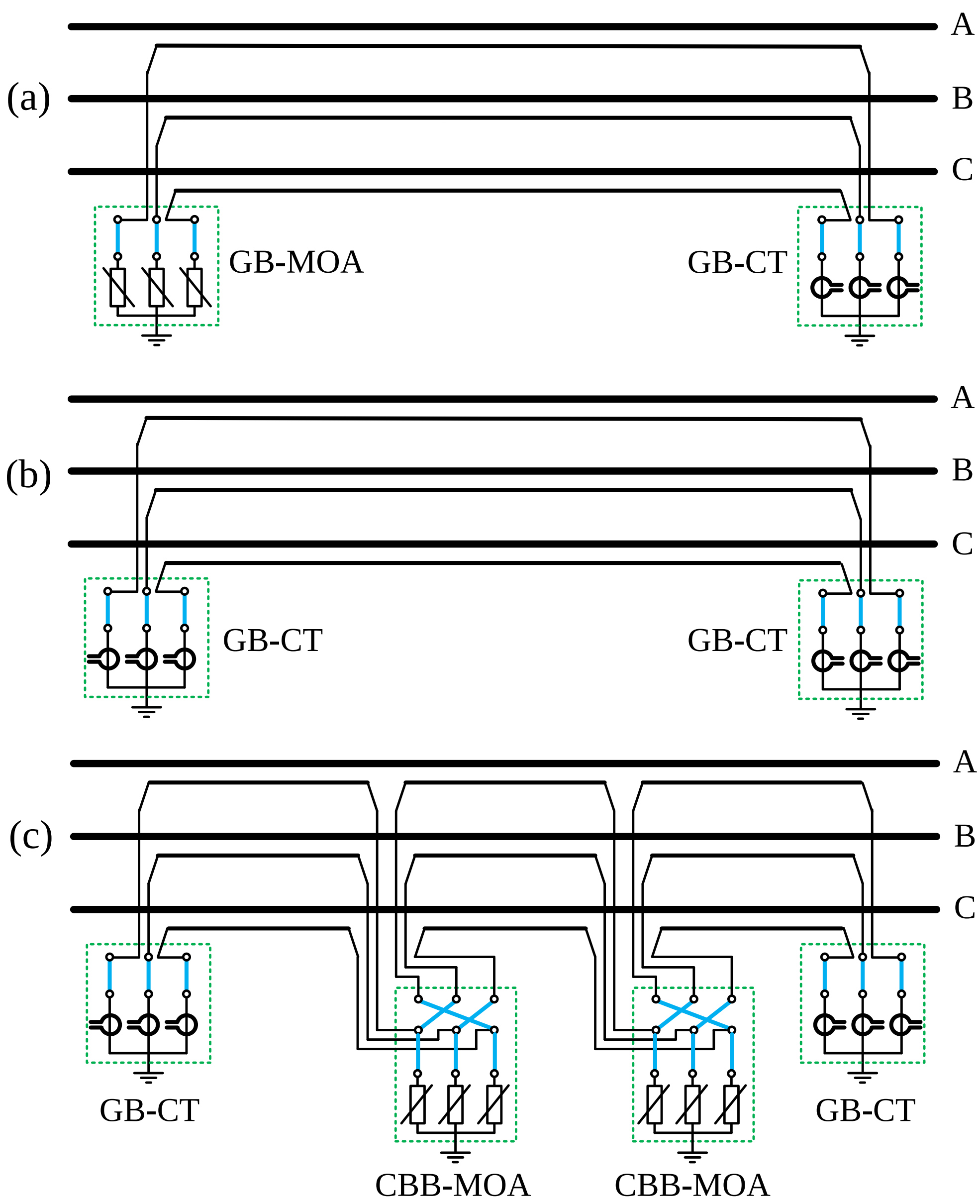

Fig.2. Main bonding/grounding schemes for single-core cable screens:
(a) – one-side grounding of screens;
(b) – both-sides grounding of screens;
(c) – both-sides grounding of screens with their cross-bonding.

On a mixed line, a LAR ban must be formed if there is damage on the cable section. In turn, the presence of damage on the cable section of the line is easy to detect by measuring the currents in the screens at their groundings. Since bonding/grounding schemes of cable screens shown in Fig.2 differ from each other in the number of screen grounding points, they will require a not the same number of special type current transformers (CT) installed inside a grounding box (GB-CT).

The easiest way is to organize a LAR on mixed lines with cable sections having one-side grounding of the screens, i.e. only one place where the screens are grounded (Fig.2a). If the screens are grounded at several points at once (Fig.2b and Fig.2c), the identification of the damaged section of the mixed line and the organization of the LAR will be somewhat more difficult. Let's look at these issues in more detail.

IV. AUTOMATIC RECLOSURE FOR ONE-SIDE SCREENS GROUNDING

It was noted that the vast majority of mixed lines have only short cable sections, and mainly they are at the points where the lines enter the switchgear of stations and substations.

In the article [2] and other literature it is shown that for short cable lines (with length less than 500 m) it is best to use one-side grounding of screens (Fig.2a). Therefore, for cable entries of overhead lines to switchgears, this particular grounding scheme is used most often, because the cable entries are just of small length, up to several hundred meters.

On cable entries made by single-core cables, the screens could be grounded from the side of the switchgear using a grounding box GB-CT, which has three single-phase current transformers (Fig.3). From the side of the overhead line the cable screens are connected to the line tower through three surge arresters, placed in a special grounding box (GB-MOA).

Sometimes, it is advisable to lay a metal bus along the cable section [3], which allows:

– to reduce the AC 50 Hz voltage induced on the screens when short-circuits external to the cable appears (on the overhead section of the mixed line or in the external network);
– to reduce the grounding resistance of the tower and level its potential with the potential of the grounding of the switchgear (in order to minimize the risk of damage to the MOA in the GB-MOA box during lightning discharges into the overhead line tower or during short-circuits on the territory of switchgear.

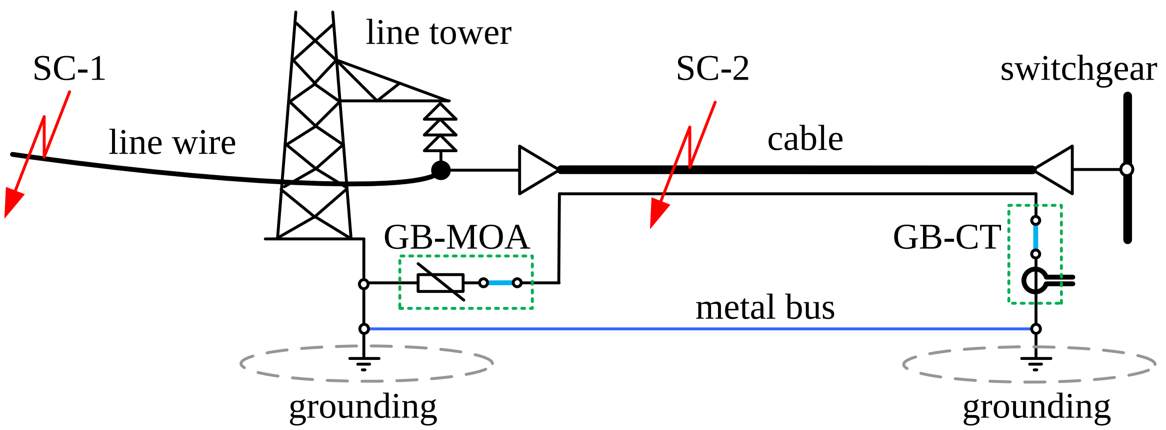

Fig.3. Cable entry of the overhead line into the switchgear (it is shown only one phase).

Fig.4a shows the directions of the short-circuit current flow depending on the location of the short-circuit in relation to the cable section having a one-side grounding of the screens. As can be seen, in case of an external short-circuit (for example, in case of a short-circuit in the overhead section of the line), there is no current in the cable screen, whereas if the cable is damaged, a short-circuit current will flow at the grounding point of the emergency phase screen. Therefore, for overhead lines with cable entries, the identification of the damaged section can be performed very simply – it is enough to install current measuring transformers from the side of the switchgear into the grounding circuit of single-core cable screens, and upon the appearance of a 50 Hz current in them, give the command to ban the LAR.

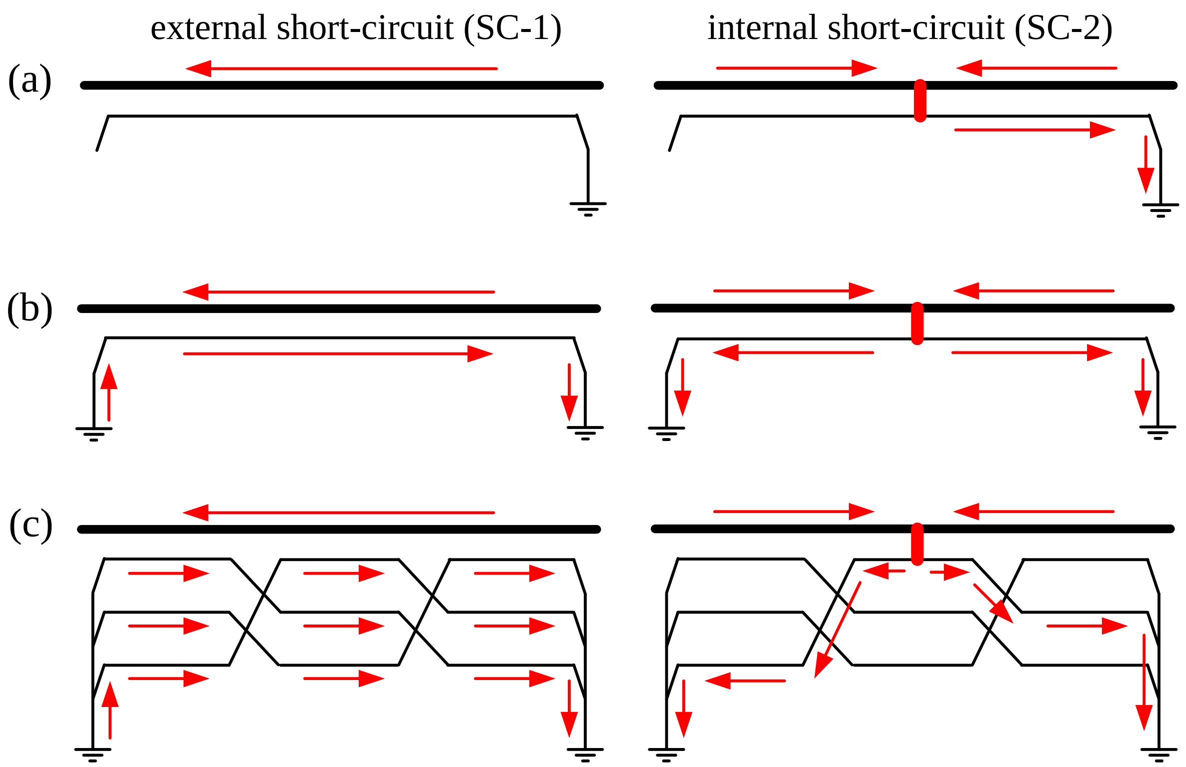

Fig.4. Currents in the screens of single-core cables, depending on the place of damage:
(a) – case of one-side screens grounding (only the damaged phase is shown);
(b) – case of two-sides screens grounding (only the damaged phase is shown);
(c) – case of the screens cross-bonding (all three phases are shown).

If three phases were damaged at once on the cable section and a three-phase short-circuit occurred, then the current will be in the screen of each of the three single-core cables (currents I_{SA}, I_{SB}, I_{SC} in Fig.5), but the total current I_{SABC} will be absent due to compensation of I_{SA}, I_{SB}, I_{SC}. For this reason, it is necessary to control the currents in the screens separately in each of three phases, i.e. three separate single-phase current transformers CT are needed, and not one common three-phase current transformer (in Fig.5 it is designated as CT-3). The presence of three CT also allows you to issue a command to ban the LAR in phases, i.e. it is required for the organization of the single-phase LAR of the mixed line.

So, to set up an LAR on a mixed line having a cable section with one-side grounding of the screens, a current transformer must be installed in the screen for each of the three phases at the grounding. The appearance of a noticeable current of current transformers in one of the three phases of the cable means that it is necessary to prohibit the LAR of the phase where it is fixed (or to prohibit the LAR of the entire line if there is no single-phase LAR on it or if there is damage in several phases at once).

If the one-side grounding of the screens is performed from the side of the switchgear, then there is no problem in choosing a place for the CT and in organizing the transmission of information from these CTs to the line relay protection devices. If one-side grounding is applied on a cable section that is not a cable entry, but located somewhere at a distance from the switchgear (case Fig.1c), then it will be necessary to solve problems of placing the CT on the line tower and organizing the communication channel of these CTs with one of the relay protection terminals on line's switchgear.

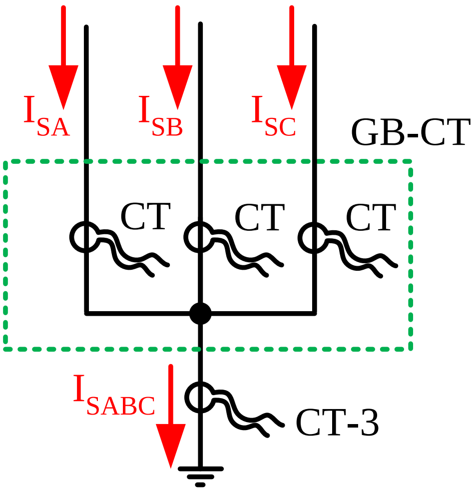

Fig.5. The grounding of cable screens using current transformers (CT).

V. AUTOMATIC RECLOSURE FOR BOTH-SIDES SCREENS GROUNDING

The vast majority of mixed lines have only short cable sections that are cable entries. For them, the use of one-side grounding of screens is recommended, and, as a result, the organization of the LAR can be done very simply – by installing three current transformers at the place of grounding of the screens on the territory of the switchgear.

For some mixed lines, of which there is a clear minority, cable sections have more complex screens bonding/grounding schemes (from the point of view of setting up the LAR) – this is either both-side grounding (Fig.1b) or the screens cross-bonding (Fig.1c). Each of these schemes has its own features.

With both-sides screens grounding, AC 50 Hz currents are present in the screens and in their grounding points in many cases. Firstly, currents are in the case of a short-circuit in the cable (when the short-circuit current passes from the core directly into the screen through the damaged cable insulation). Secondly, currents could be in the case even with no damage of the cable insulation (these currents are induced in the screens by the magnetic field of the currents of the cable cores [2]):

– in the normal steady-state operation of the cable line;
– when there is a short-circuit external to the cable line.

As follows from Fig.4b (case of damage external to the cable or in normal operation) the currents at the screen grounding of any cable phase are equal to each other, but have the opposite sign (in other words, the sum of these currents will be zero). If the internal damage occurs in the cable, the sum of the currents will be equal to the network short-circuit current.

So, to set up a LAR on a mixed line having a cable section with both-sides grounding of the screens, for each of three single-core cables at both ends, a current transformer must be installed in the screen (one at the beginning of each single-core cable and the other at its end), and their readings must be summed up. The appearance of a noticeable total current of a pair of current transformers in one of the three phases of the cable section means that it is necessary to prohibit the LAR of the entire phase of mixed cable-overhead line (or it is necessary to prohibit the LAR of the whole line if there is no single-phase LAR on it).

VI. AUTOMATIC RECLOSURE IN CASE OF SCREENS CROSS-BONDING

When cross-bonded, the cable screen loses its belonging to a particular phase of the cable (A,B,C) since the screen is located either next to one phase or next to another along the cable route. Therefore, if for LAR purposes we use the described idea of current control in the cable screen groundings, it is difficult to organize single-phase LAR on mixed lines with cable section having screens cross-bonding. Because of this, we will continue to talk only about the ways of organizing three-phase LAR.

In life, there are two types of screens cross-bonding: the ideal screens cross-bonding and non-ideal. With an ideal screens cross-bonding in the normal steady-state operation of the cable line, there are no currents in the screens, and the conditions for this are:

- equality of lengths of cable sections between the nodes of cross-bonding;
- the same distance between the phases of the cable line in its sections between the cross-bonding nodes (everywhere the phases are laid in a triangle or everywhere in a row).

There are almost no cases of ideal cross-bonding, and therefore, in the screens the AC 50 Hz induced currents still pass in normal mode, although they are noticeably less than with both-sides grounding of screens without their cross-bonding. If we take any of the three screens of the cable line with a non-ideal cross-bonding, then at both places of its grounding the currents are equal to each other in magnitude, but of the opposite sign (Fig.4c, left).

With a short-circuit external to the cable, the currents at both grounding of any of the three screens are also equal to each other in magnitude but with opposite sign (Fig.4c, left).

In other words, both in normal mode (with an ideal or non-ideal cross-bonding) and with an external short-circuit, the sum of both currents of any of the three screens will be zero. If the damage occurred in the cable (internal short-circuit), then the sum of these both currents will be equal to the short-circuit current of the network (Fig.4c, right).

So, to set up an LAR on a mixed line having a cable with screens cross-bonding, for each of the three screens at both ends, a CT must be installed, and their readings must be summed up. The appearance of a noticeable total current of a pair of CT in any of the three cable screens means that it is necessary to ban the LAR of the entire mixed cable-overhead line (we are talking only about three-phase LAR, since it is very difficult to establish single-phase LAR for cross-bonding). During installation, it is important to correctly divide the six CT into pairs for the subsequent summation of their readings, because each of the screens on one of its sides belongs to one single-core cable, and on the other side – to another.

VII. CONCLUSIONS

Currently, a large number of overhead lines are operated, which have cable sections. Over the years, the number of such lines will grow. For the line overhead sections, automatic reclosure is a good way to increase the reliability of power supply to consumers, and for cable section, on the contrary, it is extremely undesirable. Therefore, design and operating personnel have a question about how to organize automatic reclosure on such mixed lines.

While some experts propose to completely abandon the automatic reclosure for mixed lines, others categorically disagree with them, but to identify the damaged area they offer unnecessarily complex, unreliable, expensive technical solutions that require the purchase of foreign equipment. At the same time, as it was shown above, for the adjustment of mixed line automatic reclosure, it is quite enough to have a simple circuit for measuring currents in the screens of three single-core cables, using for these purposes successfully produced by the domestic industry special grounding boxes with current transformers inside.

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