Improving the reliability of combined overhead and cable power lines by organizing smart autoreclosing

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Abstract. The application of combined overhead and cable power lines (OCPLs) of 110 kV voltage rate and higher call for new features for power system protection and automation devices. One of the most urgent is the problem of autoreclosing (AR) of OCPL. One or another solution to this problem significantly affects the reliability and efficiency of the OCPL operating. In many countries, both non-selective AR and selective AR are used. A method of selective AR of OCPL based on traveling waves is proposed, which increases the reliability of OCPL protection and automation. The method uses a special procedure of traveling wave pattern classification for faulted section identification.

1 Introduction

Nowadays, OCPLs are becoming more common in large cities. This is due to the need to replace some overhead lines (OL) with underground cable lines (UCL). Another reason is constraints to the construction of new high-voltage OLs in dense urban areas. Capital costs for UCL construction is higher than for OL construction. This causes the practice of hybrid lines construction comprising OL sections and UCL sections. In contrast, many challenges are appearing connected with OCPL operation in normal and emergency conditions. One of the most crucial challenges is AR of OCPL.

It is well known that AR of power lines is an effective way to increase the reliability and the sustainability of power transmission. However, there is additional damage may be caused by re-energization OCPL without faulted section identification (non-selective AR of OCPL) in case of faults on UCL. Therefore, power line dead-time reduction achievement due to AR is counterbalanced by faulted UCL re-energization probability. Accordingly, the non-selective AR of OCPL is not the right way for power supply reliability increasing.

Thereby it is relevant to employ selective AR of OCPL, which performs specified faulted section identification procedure before reclosing attempts and block AR if a fault on UCL. In this meaning, the paper's goal is to analyze and outlook existing methods of AR of OCPL and to evaluate prospects for their application.

2 Classification of methods of selective AR of OCPL

There are several faulted section identification methods for selective AR of OCPL plenty large enough to classify them by operating principle. (Fig. 1):

1) The first class of methods is differential in which faulted section identified with signals measurements by the ends of controlled zones (for example, by ends of cable section) [1]–[3]. There are differential methods:

- a) Based on measuring of phase currents [1],[2];
- b) Based on measuring currents in shields of cables [3];

2) Another class of selective AR of OCPL is distant methods. Distant methods based on remote measurements of controlled signals by one or two ends of the line. The faulted section can be estimated using fault locating methods, or it can be identified with the use of specified methods and algorithms of faulted section identification [4]–[7]. Distant methods classified on:

- a) Passive methods, which also can be classified on:
 - Single-ended [4], [5];
 - Double-ended (or multi-ended in case of many junctions on OL) [6];
- b) Active methods [7].

Fig. 1. Classification of methods of selective AR of OCPL

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Let us consider the features of the various methods of AR of OCPL and make a comparative analysis.

3 Differential methods of selective AR of OCPL

Differential methods are based on the comparison of signals (usually current signals) by the ends of UCL or OL sections (Figs. 3-5, a, b). This class includes a method for determining the faulted section of OCPL by comparing currents by the ends of UCL sections of OCPL [1]. Reference [1] proposes installing current transformers (CTs) at each OL to UCL transition. There are current sensors (CSs) connected to secondary windings of these CTs. CSs measure signals and transmit information through a special communication channel to the main device installed at the power substation (PS).

In reference [2], a technical solution based on special optical current sensors (using the Faraday effect) was applied. These sensors are sequentially connected by optical fiber with an electronic-optical device (main device) installed at one of the line terminals. The main device thus obtains the current measurements at the UCL section ends via an optical fiber connection. It calculates the differential current of the UCL section and determines the external or internal fault. If there is an internal fault for the UCL section, the AR is blocked.

Another differential method is to supervise the currents in the cable shields. In this case, CTs are used installed on the cable shield grounding conductors [3]. CT supply current to a measuring device, which transmits the current signal parameters via an optical fiber link to the main device with selective AR logic.

The advantage of differential methods is the high security of determining the faulted section (ensuring the almost absolute selectivity of the AR of OCPL) and the applicability for various configurations of the OCPL. The main drawback is the need to install additional equipment both at the line terminal and at the OL to UCL transition (current transformers, current sensors, data collection and data transmission devices) and to organize a special communicational channel. All this makes the application of differential methods an expensive technical solution. Also, it will be shown below that the number of equipment required is directly proportional to the number of UCL sections. Therefore, the reliability of these technical solutions decreases with the growth of UCL sections, and the engineering-and-economical costs of installation, commissioning and maintenance increase. Also, it may be required for power supply and heating the devices at the OL to UCL transition, which leads to even more complications and costs of equipment used.

4 Distant methods of AR of OCPL

Distant methods of selective AR of OCPL can be described in terms of their operational principle as methods based on measurements of signals at the line terminals, not at ends of UCL or OL sections (i.e. the measuring point is remote from the controlled sections of

the OCPL). Distant methods can be classified according to the type of controlled signals into passive methods (Figs. 3–5, c–e) and active methods (Figs. 3 and 5, f). Passive methods based on monitoring current and voltage transients naturally occurring due to faults on the line (for example [4]–[6]). The faulted section can be estimated via fault locating methods or by the use of specified faulted section identification algorithms [5]. Active methods based on the injection of specified signals (high-frequency signals as a rule) into the line or its section (for example into the shield of UCL). The faulted section is monitored through artificial signal parameters (presence or absence of signal, signal energy, etc.).

For the simplest implementation of the single-ended distant passive method of selective AR, one can use zones of nonpilot stepped distance protection or impedance-based fault locating information. The main drawback of this method is the AR blocking in a large part of the OL sections due to the need to apply margin when setting the blocking region. The reason for this is the insufficient accuracy of impedance-based techniques.

The way for eliminating drawbacks mentioned before is to use methods based on electromagnetic transients monitoring and traveling wave fault locating having enough accuracy for selective AR. There is a technique of adaptive (selective) AR based on double-ended traveling wave fault locating adapted for OCPL [6] (Figs. 3-5, c). Calculated fault location used for decision making about faulted section and, therefore, AR blocking if fault detected in block region.

4.1 Selective AR of OCPL based on transients monitoring

It is known that fault cause rapid discharge of the line that generates a steplike change of voltage in the fault location. Thus, the first stage of the transient process begins, which connected with traveling waves propagation along the line length from the fault location. Inhomogeneity of OCPL, which is generally due to OL to UCL transitions, leads to many reflections of traveling waves during propagation along the line. Therefore, there are additional high-frequency transients in the voltage and current signals. These transients carry information about the faulted section of the OCPL and fault location. Studies conducted on simulation models [5] are showing that behavior of electromagnetic transient processes and particularly traveling wave transients depend on the faulted section of OCPL. Thus, it is possible to identify the faulted section by classification of transient current and voltage signals.

Therefore, distant passive selective AR methods based on transient process estimation are looking promising. It should be noted that it is possible to use both single-ended measurements (Figs. 3-5, d) and double-ended (or multi-ended in case of junctions on OL section) synchronizeless measurements (Figs. 3-5, e). At the same time, conventional traveling wave fault locating methods aren't suitable for OCPL. Hence it is advantageous to develop special signal processing algorithms and faulted section classification methods.

In addition to the above, single-ended measurements based methods require more complex signal processing and classification procedure in contrast to double-ended based methods having much fewer requirements for signal processing. Nevertheless, double-ended methods require communication channels between substations. Thus, the benefit of single-ended methods application is the number of equipment reduction down to one device (except measuring transformers), and the drawback is signal processing algorithms computational costs increasing. It is worth noting that the highlighted drawback is not crucial at present due to the ongoing growth of the computational power of microprocessor-based units.

Fig. 2. Dependence of filtered current signal measured at one of the line terminals from the faulted section for OCPL configuration OL-UCL-OL.

Several faulted section identification algorithms were developed based on the above principle. These methods are classified as distant passive methods of selective AR. One of the methods is to apply single-ended measurements and pattern classification techniques [5]. The method essence is special signal processing of current or voltage transients and traveling wave pattern forming (like shown in fig. 2). This traveling wave pattern then compared with reference patterns preliminary computed via simulation modeling of faults in OCPL and stored. The comparison is performed with correlation signal processing [5].

4.2 Distant active methods of selective AR

Active distant methods include the selective AR method with the induction of a superimposed signal into the cable shield [7] (pict. 3,5, f). According to this method, a high-frequency signal generator is connected to the cable sheath through an inductive coupler. The signal with a selected frequency of higher harmonics is induced into the cable sheath. Thereby there are high-frequency electrical oscillations in the cable sheath. During normal operating mode of OCPL, and also in the case of fault on OL, there is no path for the current and superimposed signal is not induced to the cable core. In opposite, if there is insulation breakdown and cable core having been shorted to the sheath, the imposed electrical signal is propagating along the line to the power substation and can be measured by a protection device. The analog-to-digital conversion with a high sampling rate is required, 80-256 samples per cycle as an instance.

It should be noted that the impedance of an external electrical system increases with the rise of imposed signal frequency, therefore, it is rather to measure voltage signals than current signals. At the same time, the frequency of the imposed signal is limited by a voltage transformer bandpass and a protection device sampling rate.

The drawbacks of the method are the need to use special high-frequency signal source and the constraints on OCPL configuration (only UCL-OL and UCL-OL-UCL configurations).

5 Comparison of selective AR schematics

For comparison methods of selective AR in terms of reliability, it is appropriate to consider corresponding technical solutions. Evaluation of the reliability of the faulted section identification algorithms is difficult and depends on the consideration of particular cases and the probabilities of events. Therefore, the methods of selective AR will be evaluated by comparison of a set of the elements constituting the schemes of selective AR. To carry out such an assessment, Figures 3–5 show the schematic solutions of selective AR for three OCPL configurations: UCL-OL, OL-UCL-OL, UCL-OL-UCL. Figures 3-5 show the differential methods of selective AR (a, b) and the distant methods: passive (c, d, e) and active (f). These selective AR methods are shown in the figures in the order of their description in the text above. It is worth noting that in the case of the OCPL configuration OL-UCL-OL, the distant active method [7] is inappropriate to use due to the constraints of the organization of the imposed signal source at the UCL-OL transition that is remotored from the power substation.

Fig. 3. Schemes of selective AR for OCPL configuration: UCL-OL.

In figs. 3-5, the following abbreviations are introduced: UCL - underground cable line, OL - overhead line, CT - current transformer, VT - voltage transformer, CS - current sensor (signals measuring, processing and transmitting device), D - main device of selective AR, CCh - communication channel, Tr - transmitter (imposed signal generator), IC - special signal transformer (inductive coupler), CTR - common time reference system.

Fig. 4. Schemes of selective AR for OCPL configuration: OL-UCL-OL.

We also assume that the elements of the circuit for the reliability evaluation are connected in series. Let us write down the expressions of the probability of failure-free operation for the schemes of selective AR (Figs. 3-5, a – f). We also assume that the failures of elements are independent in occurrence. Then for the schemes on figs. 3-5 (a – f), we can write expressions (1) - (3).

For the «UCL-OL» configuration:

$$p_{sch.a,b} = p_D (p_{CT} \cdot p_{CS})^2 \cdot p_{CCh} \quad (1.1)$$

$$p_{sch.c} = (p_D \cdot p_{CT} \cdot p_{TS})^2 \cdot p_{CCh} \quad (1.2)$$

$$p_{sch.d} = p_D \cdot p_{CT} \quad (1.3)$$

$$p_{sch.e} = (p_D \cdot p_{CT})^2 \cdot p_{CCh} \quad (1.4)$$

$$p_{sch.f} = p_D \cdot p_{CT} \cdot p_{VT} \cdot p_{Tr} \cdot p_{IC} \quad (1.5)$$

For the «OL-UCL-OL» configuration:

$$p_{sch.a,b} = p_D (p_{CT} \cdot p_{CS})^2 \cdot p_{CCh} \quad (2.1)$$

$$p_{sch.c} = (p_D \cdot p_{CT} \cdot p_{TS})^2 \cdot p_{CCh} \quad (2.2)$$

$$p_{sch.d} = p_D \cdot p_{CT} \quad (2.3)$$

$$p_{sch.e} = (p_D \cdot p_{CT})^2 \cdot p_{CCh} \quad (2.4)$$

For the «UCL-OL-UCL» configuration:

$$p_{sch.a,b} = p_D (p_{CT} \cdot p_{CS})^4 \cdot p_{CCh1} \cdot p_{CCh2} \quad (3.1)$$

$$p_{sch.c} = (p_D \cdot p_{CT} \cdot p_{TS})^2 \cdot p_{CCh} \quad (3.2)$$

$$p_{sch.d} = p_D \cdot p_{CT} \quad (3.3)$$

$$p_{sch.e} = (p_D \cdot p_{CT})^2 \cdot p_{CCh} \quad (3.4)$$

$$p_{sch.f} = (p_D \cdot p_{CT} \cdot p_{VT}) \cdot p_{Tr} \cdot p_{IC}^2 \cdot p_{CCh} \quad (3.5)$$

Fig. 5. Schemes of selective AR for OCPL configuration: UCL-OL-UCL.

For analyzing figures 3-5 and expressions (1) - (3), we assume the probability of failure-free operation of the similar elements is the same. Thuswise, it can be seen that for the differential methods the amount of equipment required, as well as the probability of scheme failure, greater than for distant methods. It can also be noted that in the case of distant methods of selective AR (Figs. 3-5, c-e), with the exception of the active method with signal induction into the cable shield (Figs. 3-5, f), the number of equipment required does not change when increasing the number of cable sections. In contrast, for the differential methods (Figs. 3-5, a, b), the number of required equipment increases with the growth of cable sections number, and the probability of failure-free operation decreases.

The conducted comparison and estimation of the selective AR methods seems to be sufficient for a preliminary conclusion that distant methods of selective AR are the most promising for their further development. This is due to the distant methods have less cost and seem more reliable for technique implementation. It is also worth noting that the development of traveling-wave based methods of selective AR makes it possible to further use signal estimation algorithms for implementation in advanced traveling-wave based protection devices.

6 The logic of distant methods of selective AR

It is possible to implement selective AR methods with the use of the device of selective AR together with existing microprocessor devices of power system protection with breaker automatic control features. Thereby general logic of selective AR is as shown in fig. 6. The logic of selective AR provides capability for using both the fault locating algorithms and the faulted section identification algorithms. The setting of operating mode provides the choice. The calculated fault location (FL) is applied to inputs of comparison elements (fig. 6) where the fault location entrance in the blocking region is checked [6]. The blocking region is established by two settings: the first blocking region initial point (BRI1) and the first blocking region end (BRE1). Comparison elements are joint by the AND element, which output connected with one of the inputs of the OR element. The other inputs of the OR element is for different blocking regions joining up in the main logic of selective AR. If the faulted section identification algorithm will provide the "fault on UCL" signal or calculated fault location will hit into one of the blocking regions, then AR will be blocked.

Fig. 6. The block diagram of the logic of selective AR.

Developed logic scheme for AR blocking is flexible and allows one to use any fault locating techniques or faulted section identification techniques.

Conclusion

The methods of selective AR were classified by operating principles and considered in the paper with particular technique examples. Based on conducted comparison analysis there a conclusion can be made that differential methods of selective AR (fig. 3-5, a-b) can be used for the "UCL-OL" line configuration (fig. 3) and the "UCL-OL-UCL" line configuration (fig. 4). On the contrary, in the case of other line configurations (ex. fig.5), the differential methods application is unbeneficial, except particular cases when distant methods inefficient.

It is important to note that distant methods of selective AR are more viable and can be applied in most cases of OCPL configuration. However, it is advisable to use the distance active method (Fig. 3-5, f) only with the "UCL-OL" and "UCL-OL-UCL" line configurations. In the case of relatively short OCPL sections, some single-

ended distant passive methods of selective AR can be ineffective, so the use of double-ended methods is promising.

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