Longitudinal Differential Protection of Power Systems Transmission Lines Using Optical Waveguide

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Additional information is available at the end of the chapter

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Abstract

This chapter describes using optical waveguide for communication between two relays on the opposite ends of the power systems transmission line (or transmission line). Transmission lines are a very important part of the power system. Because of that, relay protection must be fast and safe. Longitudinal differential protection satisfies these requirements. Pilot wire differential relays are commonly used for the protection of short lines. The existence of the pilot wires is a disadvantage. This protection is limited to lines of a few tens of kilometers. However, if optical protection ground wires (OPGWs) are used, instead of pilot wires, the length of the line ceases to be a limiting factor. The following sections tell more about constructions, assembly and utilization of the optical waveguides in differential protection. Also, the newest algorithms of this protection are listed.

Keywords: differential protection, relay, communication, optical protection ground wires, transmission line

1. Introduction

Due to the transient stability of the power system, faults on the lines near the power plant or large substations must be switched off quickly. Longitudinal differential protection can be applied for fast and selective protection of lines.

The longitudinal differential protection principle is based on the comparison of the currents located at the beginning and at the end of the line, resulting in a quick, sensitive and simple protection concept that ensures that the faulted line is disconnected from the network. The protected zone is defined by the position of the current transformers from which signals are brought into the differential relay.

Analogue longitudinal differential protection is used for shorter, single-circuit transmission lines in double-fed networks. Pilot cable line connects secondary current transformers on the opposite sides of the protected line. A great disadvantage is the existence of pilot wire, and such protection is limited to short lines. If optical protection ground wires (OPGWs) are used, the length of the line ceases to be a limiting factor [1–3].

OPGW is a dual functioning cable performing the duties of a ground wire and also providing a patch for the transmission of voice, video or data signals. It is located at the top of the power line tower.

The second section presents a classic approach of longitudinal differential protection of transmission lines. The operating principle is explained [1–3].

The third section talks more about OPGW. It describes two different constructions of the OPGW. The same characteristics of them are mentioned and showed. The elements for connecting OPGW with the tower are enumerated and shown [4–8].

The next section describes relay protection realized with pilot wires [9–11].

The fifth section discusses the use of digital protection. The algorithms mentioned in recent works are listed. A short recapitulation is performed. Of course, all solutions or algorithms are difficult to be implemented without using OPGW [12–23].

2. Longitudinal differential protection: a classic approach

Figure 1 shows the longitudinal differential protection operating principle. If the fault occurs outside the protected zone, the left- and right-end currents have the same direction and approximate intensities, that is, their difference is negligible and the protection does not trip. Should the fault occur within the protected zone, the right-end's current changes its direction, establishing a significant current through the differential relay M, causing its tripping. Differential current is the current difference that tends to initiate operation and stabilization current is the current proportional to thought current that tends to inhibit operation.

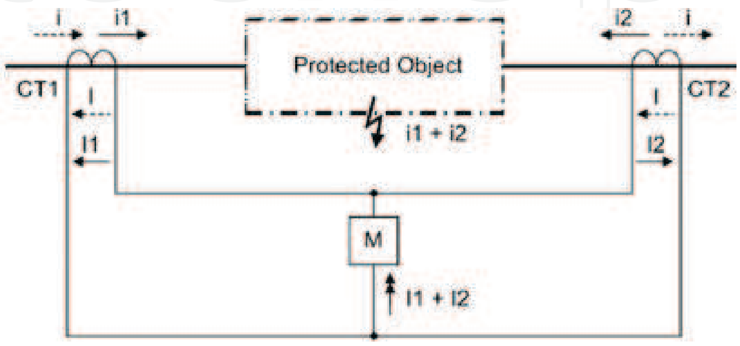

Figure 1. Longitudinal differential protection of transmission lines—Protection operating principle.

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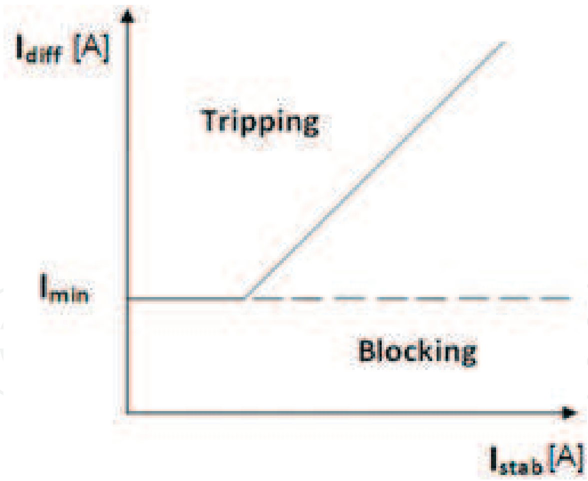

Figure 2. Differential relay tripping characteristic.

Equations (1) and (2) are used for calculating the stabilization and differential currents individually for each phase [1–3]:

$$I_{stab} = |\underline{I}_L| + |\underline{I}_R| \tag{1}$$

$$I_{diff} = |\underline{I}_L - \underline{I}_R| \tag{2}$$

with the following explanation:

IL—basic harmonic phasor of the left-end phase current.

IR—basic harmonic phasor of the right-end phase current.

Figure 2 shows the tripping characteristic of the differential relay. The minimum tripping current (I_{min}) defines the minimum relay tripping threshold and is set to 20–50% of the rated transformer current. This quantity is defined since in an actual system, in a non-fault condition, there is always a difference between the currents measured on the opposite line ends due to the current transformers' imperfection and the charging current.

The relay trips if the operating point, defined by the differential and stabilization currents' RMS values, is located within the relay tripping area (**Figure 2**) [1–3].

3. Optical protection ground wires (OPGW)

OPGW is the high-technology equipment for sending/receiving different kinds of data through electrical transmission lines.

The transmission lines are perhaps the most important part of the power system. It connects other power system elements such as power plants and substations. Electrical energy finds the way from plants to consumption, thanks to these lines. Electrical engineers found out a very easy way for data transmission using OPGW and mentioned lines.

Transmission lines have at least three phase conductors. These conductors transmit electrical power. For rated voltage above 110 kV, line towers have one or more earth wires on their top. It could be a metal wire with protective function. This earth wire conducts one part of the fault current and protects people around the tower from dangerous voltage. It serves as a lightning protection also because it is on the highest point of the tower.

OPGW could be used as the earth wire. It has the same protection functions like a metal earth wire (lightning and high over-voltages) but also includes communication that is especially important for relay protection. This fiber optic communication provides reliability in the power system protection and data transmission. OPGW construction and number of layers depend on the requirements (both mechanical and electrical). Originally, fiber is placed in the tube. Several metallic strands are located around the tube.

Nowadays, OPGW finds its place in electrical engineering. Displacing the metal earth wires by the OPGW is quite well represented. Dual function of these wires has been won.

Figure 3 shows the position of the OPGW on the top of the tower [4–8].

However, OPGW could be used for fast-data signal transmission. These signals could be protection signals, operation system data, signals for line testing and monitoring signals. Instead of this, video material or voice could be also carried out from one end of the line to another. OPGW is a multi-function conductor. The most important thing is the absence of additional investments for the trace. Transmission lines have already existed, so the only investment is in replacing the old wire with the new one.

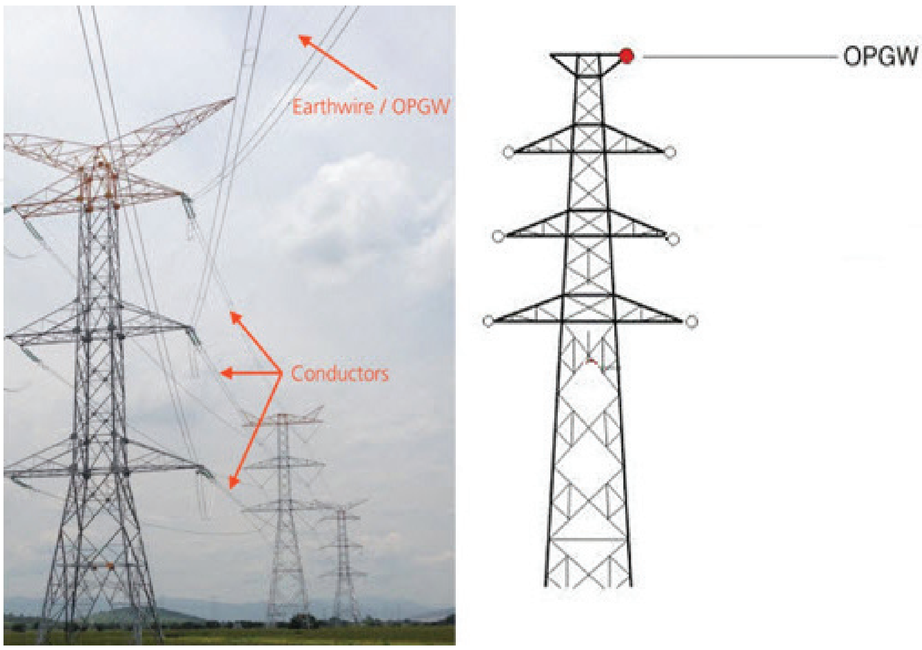

Figure 3. Position of OPGW.

3.1. OPGW cable constructions

Two types of the OPGWs are discussed. One is the central loose tube type and the other one is multi-loose tube type.

3.1.1. Central loose tube type

The steel tube is sealed and water resistant. The fibers are positioned in the center of the tube and are surrounded with water blocking gel. The stainless steel tube protects optical fibers from possible damages under abnormal operation conditions or during installation. The aluminum layer could be placed around this tube. Aluminum-clad steel wires create the external protection. This protection involves single or multiple layers of these wires. These aluminum wires provide compact construction. It has a dual function. One provides mechanical protection for sever conditions and the other one controls temperature rise during short-circuit conditions. **Figure 4** shows the cross-section of the central loose tube type.

It could be up to 48 fibers placed inside of the stainless steel tube. For easy identification, these optical wires are colored and are in different shapes. Wires are organized in many layers also. This organization provides high mechanical strength and good sag tension performance.

The core is much smaller. It is about 9 microns. This type of cable is suitable for greater distance than multimode cable. Only one light wave can travel through the fiber. This is the reason for distortion absence. The attenuation parameter for the single-mode fiber is typically 0.35 dB/km at 1310 nm and 0.23 dB/km at 1550 nm. This fiber is optimized for use in the 1300 nm & 1550 nm band [4].

3.1.2. Multi-loose tube type

The elements included in construction are almost the same. Optical fibers surrounded with water blocking gel are placed inside the stainless steel tube. This type has more than one tube. The tubes are helically positioned around the center of the cable. This is why it is called multi-loose tube type. The aluminum alloy is positioned in the external layer to give greater strength and resistance to corrosion.

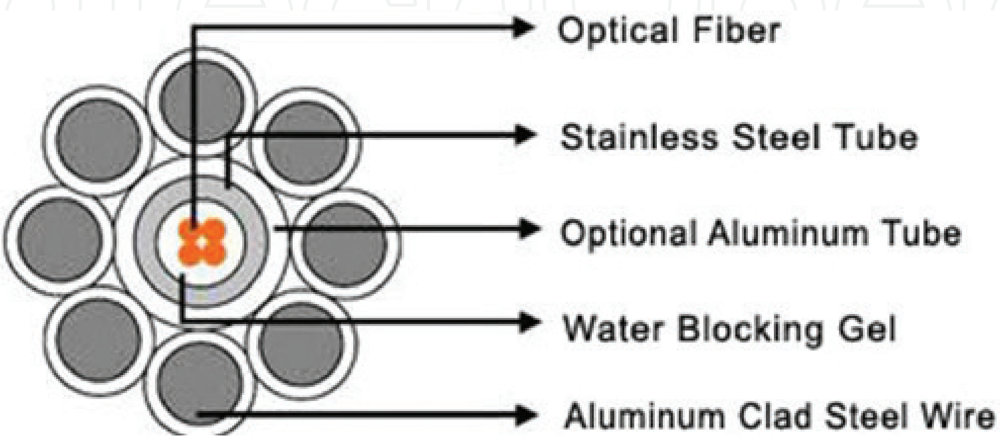

Figure 4. Central loose tube type.

The number of fibers is up to 144. The multi-loose tube type can meet the requirement of huge cross and large-current capacity.

This fiber has light traveling in the core in many rays called modes. It is made of glass fibers. The main application for multimode fibers is for short-reach optical transmission systems such as local area network (LAN) application. The attenuation parameter for multimode fiber is typically 0.8 dB/km at 1310 nm [4].

Telecom companies prefer this type of OPGW. Multi-loose tube type is good for video material transmission, internet connection and data for the SCADA system which is most important for electrical engineering. It is secure from accidental cutting due to construction work [4–8].

Figure 5 shows cross-section of the multi-loose tube type.

Tables 1–3 give some information on cable characteristics [7, 8].

3.2. OPGW cables' hardware

OPGW cables are connected with the tower and there are many elements which are used for that such as tension assembly, suspension assembly and attaching clamps and vibration dampers. These elements provide mechanical strength of OPGW and reduce oscillations. **Figures 6–9** show mentioned elements.

Sometimes, the distance between two nearest towers are longer then the length of OPGW. In that case, tension assembly has to be used. Connection with the tower is provided with tower clamps also [6].

An assembly with reinforced suspension clamp and neoprene inner covering, especially designed for OPGW cables, is shown in **Figure 8**.

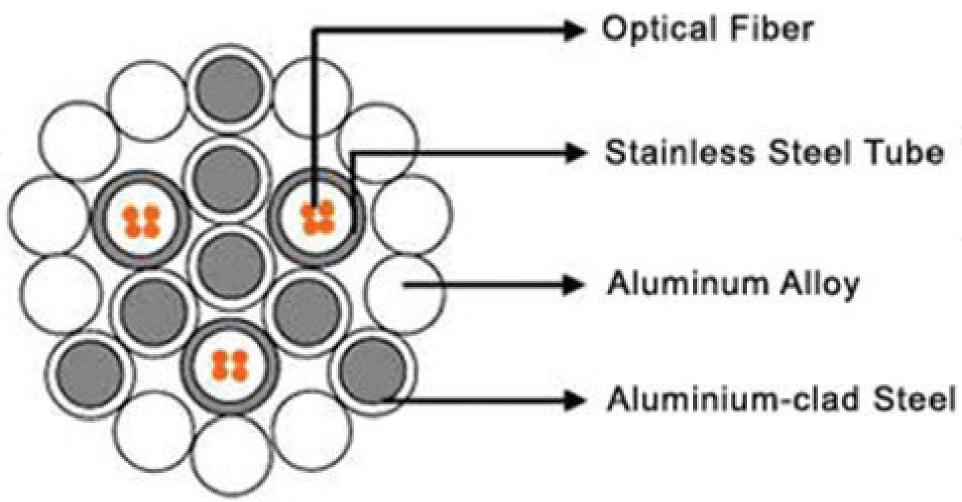

Figure 5. Multi-loose tube type.

Fiber count	Diameter (mm)	Weight (kg/km)	Short circuit capacity (KA^2s)
12	7.8	243	4.7
24	9	313	8.4
36	10.2	394	13.9
48	10.8	438	17.5

Table 1. Some characteristics of the single-layer central tube OPGW cable.

Fiber count	Diameter (mm)	Weight (kg/km)	Short circuit capacity (KA^2s)
12	13	671	42.2
24	15	825	87.9
28	16	857	132.2
36	17	910	186.3

Table 2. Some characteristics of the double-layer central tube OPGW cable.

Fiber count	Diameter (mm)	Weight (kg/km)	Short circuit capacity (KA^2s)
12	13.4	543,2	74.8
24	13.4	587,8	68.9
36	16.4	675,6	190.1
72	19.9	750	426.6
144	21.2	891,4	498.6

Table 3. Some characteristics of the multi-loose tube OPGW cable.

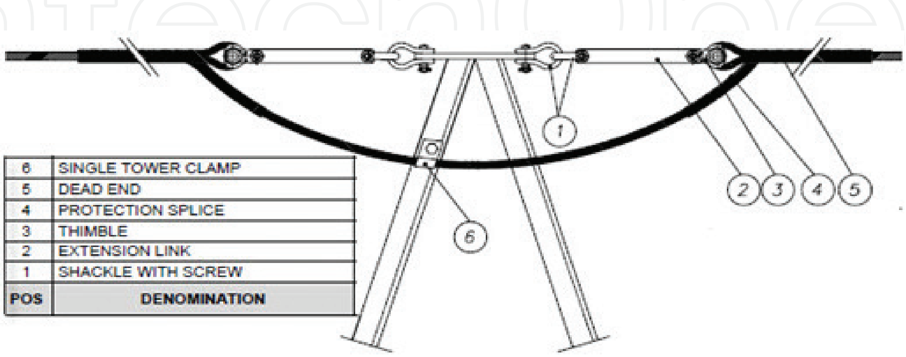

Figure 6. Double dead-end set passing for OPGW cable.

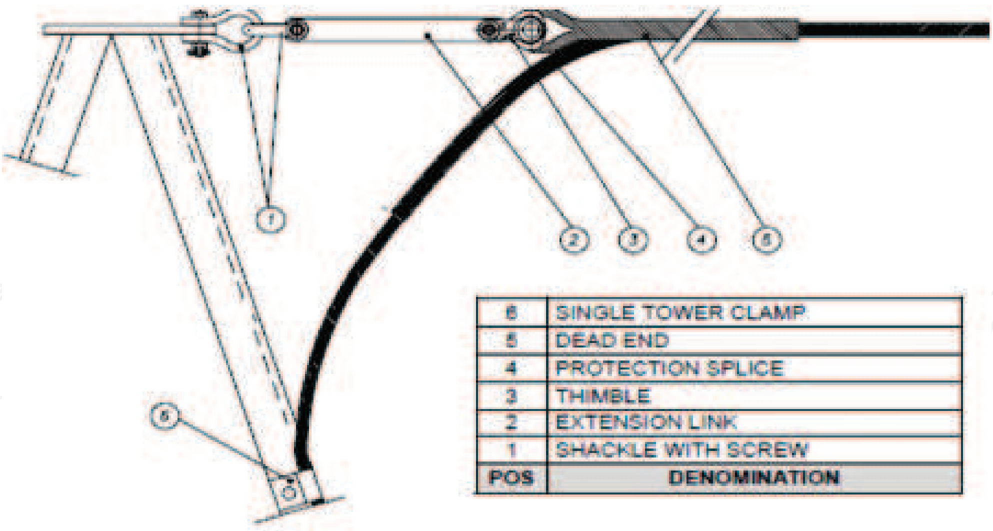

Figure 7. Single dead-end set for OPGW cable.

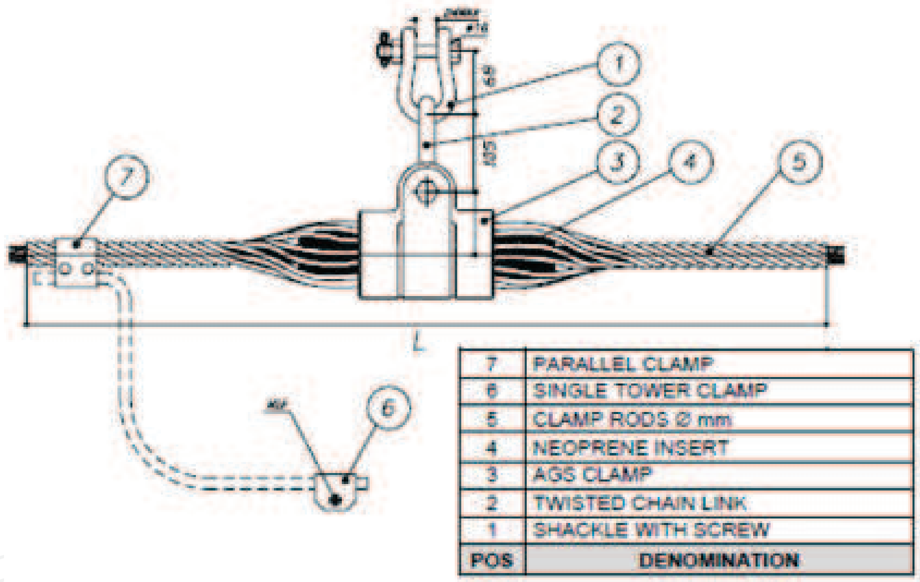

Figure 8. Suspension assembly with twisted chain link for OPGW cable.

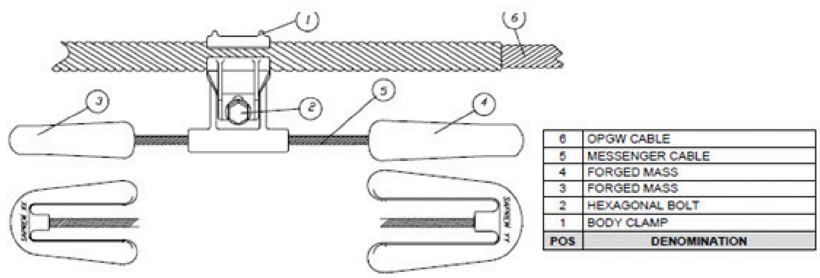

Figure 9. Damper AMG—Four resonances asymmetric Stockbridge.

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The dampers are used to absorb the cable vibrations as shown in **Figure 9**. The number of dampers is determined by the environmental conditions, the distance between towers, the type of OPGW cable and the installation parameters.

4. Differential transmission line protection with pilot relays

Pilot relays involve pilot wires. That is the main characteristic. It means that there is an interconnecting channel between two differential relays positioned at the opposite ends of the transmission line. Different types are used in practice. The distance between relays is the limiting factor. "Wire pilot", "Carrier-current pilot" and "Microwave pilot" are three different types of pilot conductors.

A wire pilot consists of a two-wire circuit of the telephone-line type. This is the easy solution because these circuits already exist as a part of the local telephone company system. Solution with a wire pilot is economical for distances up to 5–10 miles.

Beyond 10 miles of distances, a carrier-current pilot usually becomes more economical. The circuit consists of a power line as a conductor for low-voltage, high-frequency currents and the ground wire as the return conductor.

When the number of requiring pilot channels becomes larger than economic capabilities, microwave pilots are used. These are radio systems with ultra-high frequency.

Figure 10 shows the schematic illustration of the a-c wire-pilot relaying principle.

It could be a d-c connection also but more elements have to be used. **Figure 11** illustrates pilot wire d-c connection to current transformers. This connection is provided via phase sequence networks and saturating transformers. Phase sequence networks are directly connected to current transformers. Three phase currents flow in and a single-phase voltage flows out of the network [9–11].

Impedances of relay circuits are not the same rate as the pilot wire impedance. Insulating transformers match these impedances.

Pilot wire has some requirements and limitations of equipment such as the insulation capability. High voltages may occur. Insulation capability depends on the highest values that could

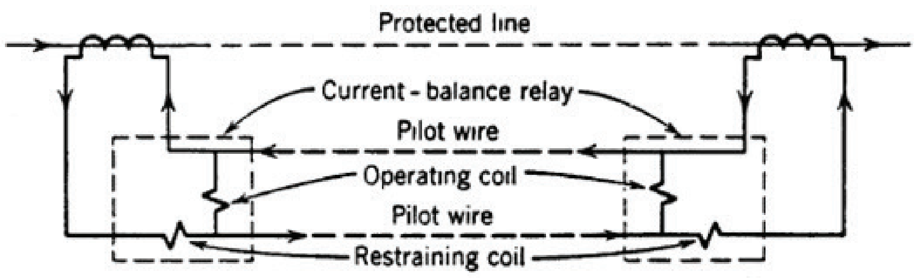

Figure 10. Schematic illustration of the opposed-voltage principle of the a-c wire-pilot relaying.

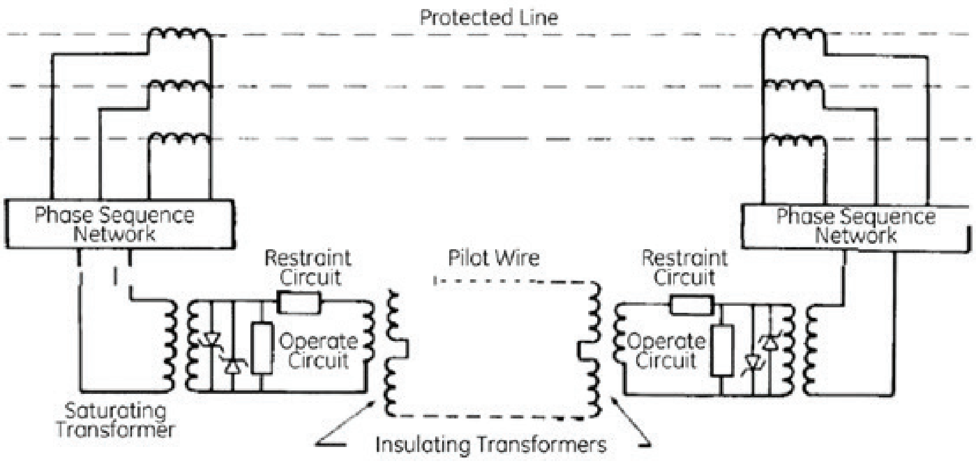

Figure 11. Pilot wire simplified arrangement.

occur. The main problem of the pilot wires is its length. It depends on loop resistance. There is a maximum value required. It is 2000 Ω. Shunt capacitance also has a limiting value. It is recommended that this capacitance be less than 1.5 microfarads.

Connection with the d-c wire pilot means that a lot of elements have to be used. This is one of the disadvantages. An a-c connection does not have these problems. Besides that, a-c connection also is immune to power swings. The good thing about d-c connection is the existence of these wires because of the telephone companies [10, 11].

5. Digital transmission line differential relays using digital communication

Natural disasters may be of significant impact on overhead transmission lines and cause communication outage related to pilot protection.

A dedicated fiber connection relies solely on optics residing within the relays to send IEEE C37.94 signaling bi-directionally, usually on a pair of single-mode strands of fiber from one relay to another. Potential sources of trouble for direct-connected current differential relay schemes normally can be traced to one of the following:

Most line-current differential relays use a 64 kbps communication interface even though designs with higher bandwidths (n × 64 kbps) are more common. The data frame length depends on the different relay designs. It varies between 15 bits and 200 or 400 bits. Sometimes it could be out of these bounds. The current data transmission has a large range also—from one to four per cycle, sometimes even more. There are some line current differential relays generally used for distribution line protection that uses slower-speed asynchronous serial communications. Presently, the use of Ethernet communications has not been widely implemented for line current differential relaying but is expected in future designs.

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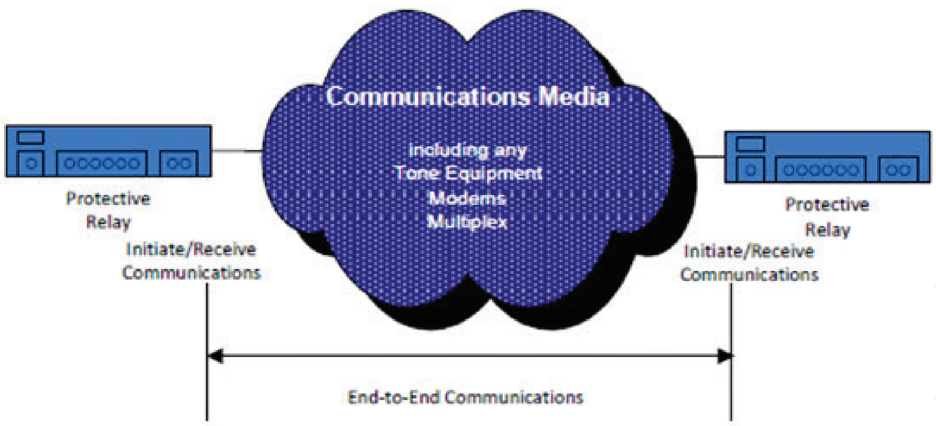

Figure 12. Protective relaying communications.

The communication channel can be over a dedicated fiber or over a multiplexed network, as shown in **Figure 12**. The dedicated fiber connection typically deploys LED or laser depending on the fiber's distance. The laser option can typically be applied for up to 100 km. The longer fiber lengths may need repeaters [12].

In order to guarantee the safe and stable operation of high-voltage transmission lines, differential protection is adopted as the main protection for the benefits of its phase-selection function and immunity to power swings and operation modes.

Many various principles for realization of the differential protection have been published in the recent literatures. The fast communication between relays installed at the opposite ends of the line is necessary [12].

There are a number of different relay measuring principles used by current differential relays:

- Percentage differential relays
- Charge comparison relays
- Power differential relays
- Alpha plane relay

These principles are briefly described in the following subsections.

5.1. Percentage differential relays

This is most like a classic approach. **Figures 1** and **2** show a basic arrangement. At each terminal, an evaluation of the sum of the local and remote current values is made in order to calculate a differential current. Under normal operating conditions or external faults, the current entering at one end of the protected circuit is practically the same as that leaving at the other end. Hence, the differential current value is practically zero and operation of the protection will not occur. For a fault on the protected power line, the differential current value will exceed the operation threshold value and the protection will operate to clear the fault. There are so many modifications of the classic approach. Some of them use negative or zero-sequence current components.

There are two types of algorithms for differential protection: those that use phasors [13–16] and those that use instantaneous values of electrical quantities [17, 18].

5.2. Charge comparison operating principle

Charging current is a capacitive leakage current on the transmission line. The operating principles of charge comparison are similar to those of the more common percentage restraint current differential type of protective relay. Current differential relays compare the total currents entering and leaving the primary protection zone. They will trip if the difference between these currents exceeds some pre-defined restraint limit. For this comparison to be made, the current differential relay at the local station has to know the identical phase current recorded at the remote station(s) for the same interval being considered at the local station. This requires precise communications delay measurement and compensation. With current differential relays that compare instantaneous values, any error in compensation causes an error in the comparison and results in a variation of the pickup point. In addition, many samples per cycle are sent to the remote station, placing a burden on the communications channel [12].

The simple system shown in **Figure 13** is assumed.

Charging current compensation is a solution which removes charging current from the measured current and hence excludes the charging current from the differential current calculation. The charging current (I_c) can be estimated on the basis of operational capacitance:

$$I_C = \frac{2 \times \pi}{\sqrt{3}} \times U_n \times f_n \times c_d \times L \times 10^{-6} \tag{3}$$

where:

I_c—charging current (A),

U_n—rated network voltage (kV),

f_n—rated frequency (Hz),

c_d—longitudinal operational capacitance (nF/km),

L—line length (km).

Then the compensated current can be calculated as follows:

$$I_x = I_x' - I_C \tag{4}$$

where:

I_x—is compensated current at terminal x,

I_x'—is measured current at terminal x.

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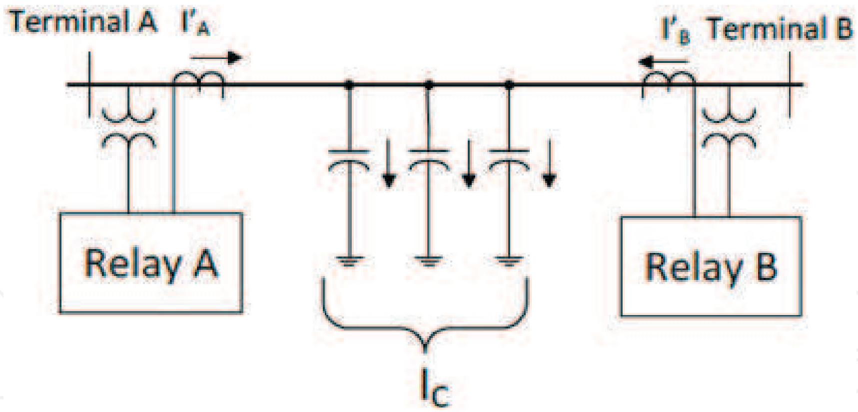

Figure 13. Charging current compensation.

Current that has a higher value should be compensated. It depends on the load flow direction. The higher value has current measured in the terminal where energy flows in.

Assuming a perfect alignment between local and remote currents, there is ±4 ms of error tolerance in the compensation. Given that line capacitance will cause a slight misalignment of the currents and that any compensation is going to have some resolution, it is practical to use ±3 ms as a limit for how much the communication channel delay can vary during normal operation without affecting the relaying. This is well within the normal operational limits of most communication channels in a dedicated fiber environment, even under adverse conditions.

5.3. Power differential relays

In addition to the classic approach, which uses current signals exclusively, there are solutions which require voltage inputs too [19–21].

Charging current is treated as the main cause of differential relay wrong operation in many papers. This current could be compensated with the power differential principle. This method proposes measuring currents and voltages at both ends of the transmission line. The original differential principle is saved. Operate and restrain values are compared but instead of currents, active powers at both ends are considered.

In this case, calculation time is reduced and length of line is not a limiting factor. These are the great advantages. Wrong operation during fault with low resistance and no faulted phase selection are the disadvantages of the mentioned technique.

There is a different method for realization of this protection based on power losses determination. It requires measuring currents and voltages at each end of the line too. Fault location could be determined in an easy way. This method compares difference in the real power at each end of the transmission line with the maximum power losses in the protected element. Every fault could be detected and the protection is secure and dependable. Fast communication between relays is very important [19–21].

5.4. Alpha plane relays

The alpha plane current differential protection principle compares individual magnitudes and angles of the currents. Magnitude and phase angle of each current at the opposite line ends are measured. According to these values, vector *r* is determined (its magnitude and angle). The alpha plane depicts the complex ratio of *IR*/*IL*, and it is shown in **Figure 14**.

Operating and restraining regions are presented in **Figure 15**. Comparison of the amplitudes and the angles lead to one of these decisions.

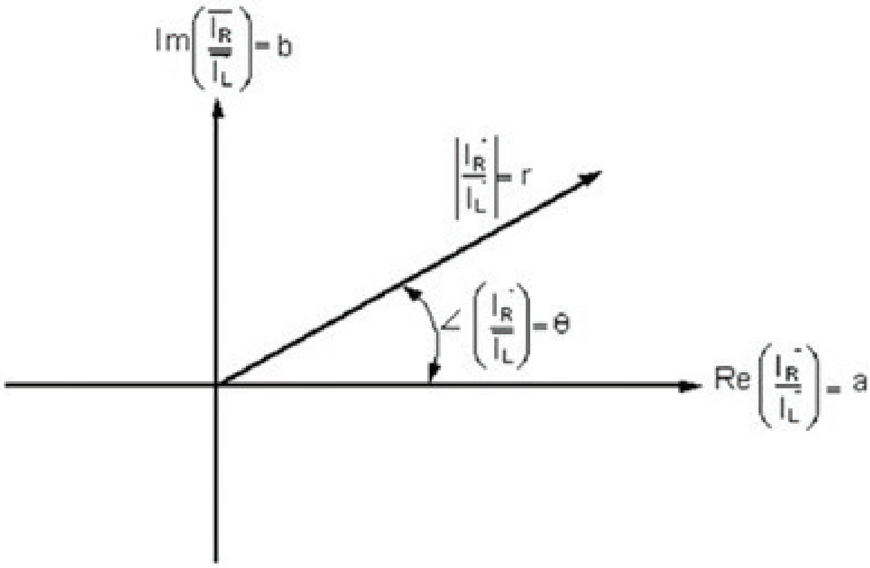

Figure 14. Complex current ratio plane (α-plane).

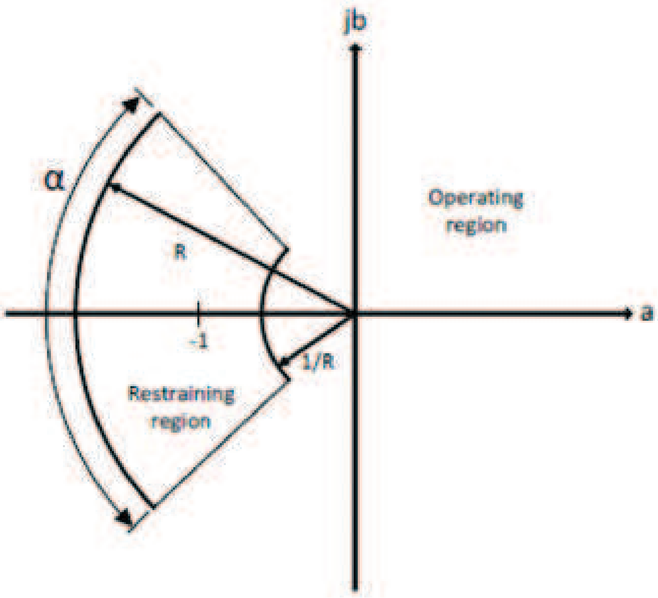

Figure 15. Current ratio plane.

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The horizontal axis variable a is the real part of the complex ratio of IR/IL, and the vertical axis variable b is the imaginary part of the complex ratio of IR/IL. In the alpha plane element, the angular setting α [°] and the radius setting R define restraining region. The first one allows the accommodation of current transformer and current alignment errors and the second one modifies sensitivity.

Data transmission delay has to be compensated. Current measuring and comparison depend on the communication channel. There are delays in two directions—transmit and receive. These delays sometimes are different. SONET/SDH systems could be the reason for this asymmetry. One technique for overcoming this problem, so-called ping-pong, involves measuring the round-trip channel delay. The communications path-delay differences are typically less than 2 ms. Delays of 3–5 ms are rare [12].

The papers that emphasize this method are authored by Almedia and Silva [22, 23].

6. Conclusion

This chapter describes using optical waveguide for communication between two differential relays on the opposite ends of the power systems' transmission line. Using the pilot wires limits utilizing this protection only for short lines. If optical protection ground wires are used, instead of pilot wires, the length of the line ceases to be a limiting factor. This chapter tells us more about constructions, assembly and utilization of the optical waveguides in differential protection. Also the newest algorithms of this protection are mentioned.

The sections present a classic approach of longitudinal differential protection of transmission lines, talk more about construction and installation of the OPGW cables and discuss digital protection algorithms. All the algorithms are difficult to be implemented without using OPGW.

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