ARCHIVES OF ELECTRICAL ENGINEERING VOL. 68(3), pp. 657–666 (2019)

DOI 10.24425/aee.2019.129348

Fault detection technology for intelligent boundary switch

Ling Liu

Department of Electrical Engineering, Shandong Polytechnic
Jinan 250104, China
e-mail: liuling95@163.com

(Received: 27.01.2019, revised: 23.03.2019)

Abstract: An intelligent boundary switch is a three-phase outdoor power distribution device equipped with a controller. It is installed at the boundary point on the medium voltage overhead distribution lines. It can automatically remove the single-phase-to-ground fault and isolation phase-to-phase short-circuit fault. Firstly, the structure of an intelligent boundary switch is studied, and then the fault detection principle is also investigated. The single-phase-to-ground fault and phase-to-phase short-circuit fault are studied respectively. A method using overcurrent to judge the short-circuit fault is presented. The characteristics of the single-phase-to-ground fault on an ungrounded distribution system and compositional grounded distribution system are analyzed. Based on these characteristics, a method using zero sequence current to detect the single-phase-to-ground fault is proposed. The research results of this paper give a reference for the specification and use of intelligent boundary switches.

Key words: fault detection, boundary switch, distribution grid

1. Introduction

In recent years, intelligent boundary switches have been widely used in the electric distribution network of China. The medium voltage (MV, typically 10 kV in China) distribution circuit section may belong to the power supply companies or users according to different areas. After the failure, it is necessary to determine whether the fault is located on the user's side or the power utility side, and then some crew will inspect and repair it. When the user line section or equipment happen to fail, if not handled properly, the entire power line fails. This expanded scope of power failure affects the normal power supply of healthy users [1] and causes disputes between the power utility and healthy users.

An intelligent boundary switch is an integrated device which integrates a load switch and a microprocessor-based controller [2, 3]. It has the function of fault detection, protection and control, communication. Installed at 10 kV overhead distribution lines, it can automatically break the single-phase-to-ground fault and automatically isolate the phase-to-phase fault. The mounting points apply to the demarcation point of responsibility in the user terminal of 10 kV distribution line. It also applies to the T-junction in the branch line which meets the requirements [4, 5]. Fault demarcation uses the principle of boundary protection [6, 7] to determine the fault interval. If the fault occurs in the user branch line or in the internal one, it usually causes a power outage on the trunk lines and other adjacent users. The intelligent boundary switch is installed on the responsibility boundary point, which can automatically remove the single-phase-to-ground fault and automatically disconnect phase-to-phase fault. It is the ideal equipment to solve the above mentioned problems [8–10].

2. Structure

2.1. Composition of intelligent boundary switch

The intelligent boundary switch is also called a watchdog. It is typically mounted at the branch line T connection (Fig. 1). The intelligent boundary switch is composed of an outdoor load switch body, a controller, a dry voltage transformer (VT) and auxiliary equipment as shown in Fig. 2. It is widely used in an automatic switching device of 10 kV city network, a rural power grid. It has the function of fault detection, protection control, and communication. Installed on a 10 kV overhead transmission line, it can automatically break a single-phase-to-ground fault and automatically isolate phase-to-phase fault.

2.2. Load switch

The load switch is a three-phase switch with porcelain insulators. A main circuit, secondary component and the operating mechanism are sealed in SF6 gas (zero gauge pressure). There is a fluid silicone rubber casing in it, so that the phase spacing can become large enough and it has excellent external insulation performances. It is well designed for a directly connecting outdoor aerial cable.

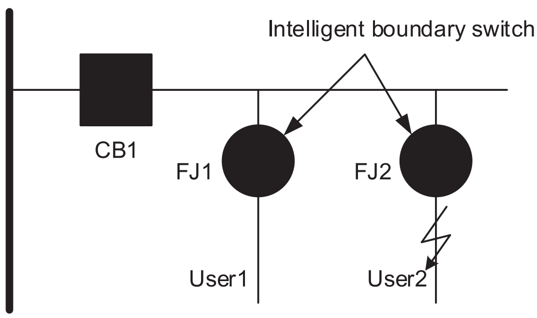


Fig. 1. Intelligent boundary load switch

Fig. 2. Intelligent boundary load switch

The load switch with an actuator (or permanent magnetism mechanism operating in a special spring), with manual and electric energy storage, manual and electric switching, hands, an electric gate function as well as external demarcation circuit breaker with three single-phase CT sets and ratio 600/5 (or a user specified ratio), the demarcation circuit breaker using an external VT, mounted on the side of the power supply, variable 10 kV/220 V, the controller and the circuit breaker operating power supply and voltage signals are provided by the VT.

2.3. Controller

The new type of boundary switch controller is a new intelligent terminal that allows communication of the local process with a master system. This device can be used in combination with each type of load switch and circuit breaker to realize the functions of protection, measurement, fault detection, isolation and communication for the distribution network. Each component of the controller is connected in a proper way, and the resources are also greatly saved.

Epoxy resin material of an outdoor controller selection box, a vertical downward operating panel and a PC mask door can prevent from erosion in temperatures between 10° and 170°, in the rain on all sides, can also prevent from corrosion and accidental injury as well as have good protection ability. A protection level is not less than IP65.

The controller applied for the distribution must be for the lowest cost and with functionality only appropriate for the applications of this level. The fundamental role of a controller is: (1) acquisition of various types of data, (2) relay protection, (3) the accumulation, conversion of data in a form that can be communicated to the master station, (4) the control of the commands received from the master station. Many of the features demonstrated by the controller are basic supervisory control and data acquisition (SCADA) functions. At the same time, relay protection is another important function of the controller. The information from a controller is delivered directly to the topology computer via the real-time distribution system network model and is used to determine a fault location. This determines the required fault information of the upstream devices in a radial network. It determines the necessary switching sequence for isolation and presents the suggested switching plan, and then, the closing of the normally open point is necessary to restore the power supply for the healthy section. This fault location, isolation and supply restoration are also the elementary functions of a controller.

3. Single-phase-to-ground fault

Distribution network faults may occur on one phase, on two phases, or all three phases. Single-phase faults are the most common fault. Almost 80% of the measured faults involved only one phase either in contact with the neutral or with ground [11, 12].

3.1. Amplitude characteristics of zero sequence current

The length of a user side line (downstream of a boundary switch) is much shorter than other parts of the distribution line. So, the capacitance of the user's line-to-ground is much lower than that of the other line-to-ground connections. In addition, the capacitance current of the user's line is much lower than that of the system side capacitance current. If the single-phase-to-ground fault occurs at different positions, there is an obvious difference in the phase and the amplitude between the user side and system side.

3.1.1. Ground faults at upstream

If the site is located in the upstream boundary switch, regardless of the system grounding or Petersen coil grounding mode, the fault frequency of zero sequence current detected boundary switch is the downstream line of distribution capacitance current. With a defined 30 mA/km for capacitance current of the 10 kV overhead line, the length of an overhead line is shorter than 30 km, so the capacitance current is less than 1 A. As showed in Fig. 3, the fault point is located upstream of the boundary switch:

$$I_B = I_{CC} = U_0 \, 2\pi f C_C < 1 \text{ A}, \tag{1}$$

where f is the frequency in hertz, U_0 is the zero sequence voltage.

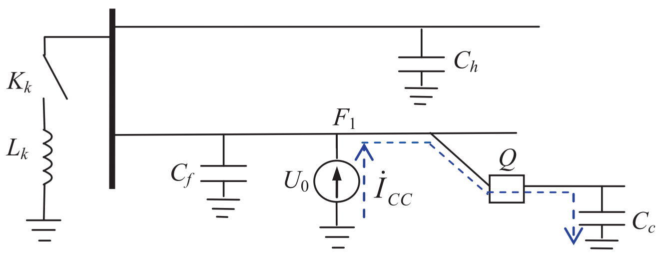


Fig. 3. Fault point at upstream of the boundary switch

In Fig. 3, Q is the boundary switch, C_C is the downstream capacitance, C_f is the upstream capacitance, Ch is the capacitance of a healthy line.

3.1.2. Ground faults at downstream

If the fault location is downstream of the boundary switch for ungrounded networks, as shown in Fig. 4, the zero sequence current of the boundary switch Q (I_B) is equal the sum of all the capacitive current of the upstream lines (I_{CU}). That is, I_B is equal to the capacitance current of the fault line in the downstream line of the boundary switch (I_{Cf}) and the perfect line to the ground distribution capacitor (I_{Ch}):

$$I_B = I_{CU} = I_{Cf} + I_{Ch} = U_0\, 2\pi f (C_f + C_h) \gg I_{CC}\,. \tag{2}$$

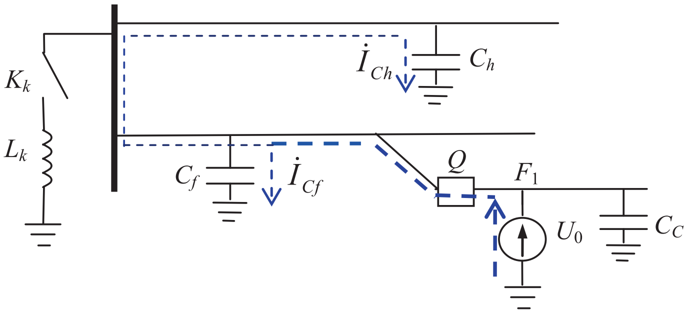


Fig. 4. Fault point at downstream on unground system

3.1.3. Ground faults at downstream on compensated networks

As shown in Fig. 5, the neutral point is connected to the ground by an inductance coil. The inductance coil is turned to balance, or near balance. If ground faults occur downstream of the boundary switch, the zero sequence current of the boundary switch Q (I_B) is equal to the sum of all the capacitive current of the upstream lines (I_{CU}) and the coil compensation current (I_L), that is:

$$\dot{I}_B = \dot{I}_{CU} + \dot{I}_L = \mathrm{j}\dot{U}_0\, 2\pi f (C_f + C_h) - \mathrm{j}\frac{\dot{U}_0}{2\pi f L_k}\,. \tag{3}$$

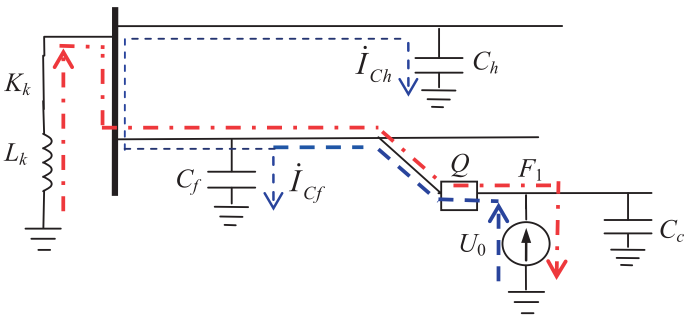


Fig. 5. Fault point at downstream on compensated networks

If the compensation coil is turned to the system capacitance, the ground fault current is zero. If the detuning of the compensation coil (named v) is about 5~20%, the zero sequence current detected by the boundary switch (I_B) can also be expressed as:

$$\dot{I}_B = \left(\dot{I}_{CU} + \dot{I}_{CC}\right) v + \dot{I}_{CC} \,. \tag{4}$$

Since the compensation coil is generally overcompensated, and the active component of the fault current is taken into account, the zero sequence current detected at the demarcation switch is still much larger than that of the downstream line to the ground.

Since the compensation coil is generally overcompensated, plus the active component in the fault current, the zero sequence current detected at the boundary switch ($\dot{I}_B$) is much larger than that of the downstream line to ground distribution capacitance current ($\dot{I}_{CC}$), that is:

$$I_B > I_{CC} \,. \tag{5}$$

3.1.4. Summary of ground fault

In a word, the zero sequence current of boundary switch is generally greater than the zero frequency current in the system side grounding, whether it is the ungrounded system or the compensated coil grounded system, while the load side is grounded.

3.2. Fault detection by zero sequence current amplitude

The zero sequence current at the boundary switch on the distribution system side ground fault is greater than that on the load side ground fault. According to this characteristic, the ground fault direction can be determined. The default threshold for fault current is:

$$I_S = K_{\text{rel}} I_{CC} \,, \tag{6}$$

where K_{rel} is the coefficient of reliability (usually about 1.3).

Then, the criterion for the direction of the ground fault is:

$$I_B \geq I_S \,,$$

the grounding fault is located downstream of the demarcation switch, that is, fault at the user side.

$$I_B < I_S \,,$$

the grounding fault is located upstream of the demarcation switch, that is, fault at the power system side.

3.3. Characteristics of zero sequence current and voltage

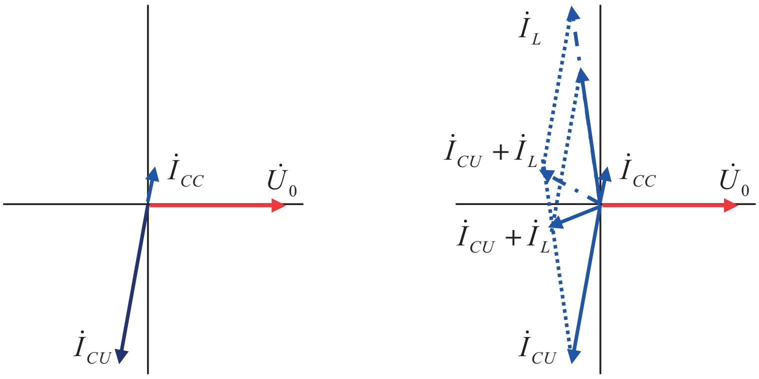
3.3.1. Phase of ungrounded networks

For ungrounded distribution systems, if the upstream line fails, as showed in Fig. 2, the current at the boundary switch is from the bus to capacitance line, and the phase of the zero sequence current is leading the phase of a zero sequence voltage. Considering the active component in the current, the leading phase is slightly smaller than 90°.

If the downstream line fails, as it is shown in Fig. 3, the current at the boundary switch is from capacitance line to bus, and the phase of the zero sequence current is delaying the phase of zero sequence voltage. Considering the active component in the current, the leading phase is slightly larger than 90°.

3.3.2. Phase of compensated networks

The compensated coil grounded system, fault line upstream, as shown in Fig. 6, is the same as an ungrounded network. The current at the boundary switch is from the bus to the capacitance line, and it is still ahead of a zero sequence voltage of about 90°.



(a) Ungrounded networks (b) Compensated networks

Fig. 6. Phase relationship between I_0 and U_0 at the boundary switch

If the ground fault point is at the downstream of the boundary, the compensated coil will increase the active current at this point. If under compensation, the delay phase of an immersed boundary (I_B) and upper boundary (U_B) is significantly greater than 90°. In the case of overcompensation, the leading phase of the I_B and U_B is greater than 120°.

3.4. Fault detection by zero sequence current phase

For a boundary switch that can simultaneously obtain zero sequence voltage and zero sequence current signals, the fault direction can be determined by the phase relation between the zero voltage of the power frequency and the phase of the currents. If the phase of the power frequency zero sequence current leading the phase of power frequency zero sequence voltage is within a preset range (>90°), it is determined that a ground fault occurs at the user side. If the phase is less than 90°, it is determined that a ground fault occurs at the power system side.

In order to adapt the ungrounded system and the compensated coil grounding system, as well as considering the transmission error of the voltage and current transformer, the criterion of the grounding fault direction of the demarcation switch can be set as:

$$100^\circ < \angle \dot{I}_B - \angle \dot{U}_0 \le 280^\circ,$$

the grounding fault is located downstream of the demarcation switch, that is, a fault happened at the user side,

$$60^\circ < \angle \dot{I}_B - \angle \dot{U}_0 \le 100^\circ,$$

the grounding fault is located upstream of the demarcation switch, that is, a fault happened at the power system side.

3.5. Performance analysis

The current amplitude method needs to preset the absolute value threshold of the fault current, which is better in the ungrounded system than in the compensated coil grounded system. In the arc-suppression coil grounding system, the arc-suppression coil is affected by the compensation current. If the load-side capacitor current is large, the setting value may be greater than the residual current value at the fault point, which will cause the rejection.

If the setting value matches the residual current value of the metal grounding fault, the relation between the transition resistance and the zero sequence current detected by the demarcation switch is:

$$\dot{I}_B = \mathrm{j}\dot{U}_0(2\pi f C_f + 2\pi f C_h - \frac{1}{2\pi f L_k} = \frac{-\mathrm{j}E(2\pi f C_f + 2\pi f C_h - \dfrac{1}{2\pi f L_k}}{1 + \mathrm{j}R_\mathrm{d}(2\pi f C_f + 2\pi f C_h + 2\pi f C_c - \dfrac{1}{2\pi f L_k}}, \tag{7}$$

where E is the voltage of the fault phase-to-ground.

As shown in Fig. 7, with the increase of transition resistance, the amplitude of the zero-sequence current will decrease. If the transition resistance is large, the fault current I_B may be less than I_S, as a result of decreased sensitivity. That is, when the transition point resistance of the fault point increases, it may not operate.

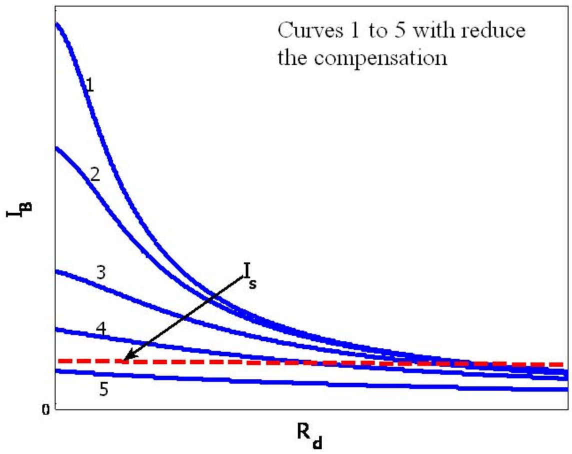


Fig. 7. I_0 changing with transition resistance and compensation

The phase comparison method of zero-sequence voltage and current does not require a preset threshold value of fault current. Phase measurement is important. If the fault current is small (far less than 1 amp), it is greatly affected by the voltage and current transformer's transmission error, and the phase measurement is inaccurate, so it is difficult to judge the fault.

In order to avoid frequent tripping caused by a transient ground fault, the zero-sequence current protection is set with a certain delay, and the operation time is removed after the fault duration exceeds the time delay. In accordance with the principle of avoiding transient faults, the delay can generally be set to 300–600 ms.

4. Phase to phase short circuit fault

There are numerous causes of faults in distribution networks. A fault between two or more phases almost always involves a short circuit. In the case of short circuits in a distribution line, very large currents can flow for a short time until a fuse or breaker or other interrupter breaks the circuit.

4.1. Short circuit fault outside the user community

When a short circuit fault occurs at the main feeder or other branches, the main feeder break will open and clear the fault.

4.2. Short circuit fault inside the user community

When there is a short circuit fault in the user community, the user boundary switch and the substation line protection cooperate to isolate the fault. Take the example as shown in Fig. 1, when there is a short circuit fault in the second user (user 2) communities, the substation outlet switch CB1 or overcurrent protection action trip, the line power fails. The intelligent boundary switch at the demarcation point (FJ2) will open and disconnect the fault line immediately after the trip to CB1. Then after the main line breaker CB1 is reclosed, the fault line will be isolated, while power supply for users on the other branches of the feeder will be recovered.

5. Conclusions

An intelligent boundary switch is installed at the responsibility demarcation point on the 10 kV overhead line. It can disconnect the faulty branch with a single-phase-to-ground fault and isolate the faulty branch with a short circuit fault, ensuring the power supply for normal customers.

When a single-phase-to-ground fault takes place, a zero-sequence current is detected to determine a single-phase-to-ground fault happened within the boundary or not. If the fault occurs on the user side, the boundary switch opens and the fault zone is isolated. If the fault occurs on the power system side or the other branch line, the zero-sequence current is much smaller than the setting value, the boundary switch does not operate.

When a phase-to-phase fault occurs within the user's community network, the boundary switch short circuit current is detected when the circuit current exceeds the overcurrent setting. After a brief delay, the boundary switch will open to isolate the fault zone.

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