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An energy differential relay for long transmission lines

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ABSTRACT

The operating speed and sensitivity of the current differential protection must be lowered in order to deal with the problems caused by the capacitive currents of the long transmission line. To solve this problem, a new energy differential relay is put forward. The proposed scheme can distinguish between internal and external faults by comparing the energies of two methods. The first method is to calculate the energy flow in the line in a short time interval. The second method is to calculate the energy consumption of distributed elements on the transmission line with the assumption that there is no internal fault on the line. Special means are adopted: use of modal quantities of voltage and current; the instantaneous voltage and current are distributed linearly along the transmission line; the instantaneous voltage and current vary linearly during a sampling interval; the sampling interval is equal to the travel time of the protected line. Thus the energies can be calculated by using the sampled values at each end of the transmission line. It has been proven that the calculated energies of the two different methods are equal when there is no internal fault on the transmission line. The performance of the proposed method has been verified by EMTP simulation tests, dynamic simulation tests and the comparison with a competitive method.

1. Introduction

It is a well recognized fact that differential protection schemes provide sensitive protection with crisp demarcation of the protection zones [1–5]. The voltage level of long-distance transmission lines is usually up to 500-kV or higher. The corresponding protection must trip as rapidly as possible to mitigate the damage if an internal fault occurs within this line. However, the line charging current component is significant and it causes a large variation in phase angle of the line current from one end to another. In traditional current differential schemes, relaying sensitivity will have to be compromised to prevent the mal-operation. Among existing technologies dealing with the impacts of the distributed capacitive current, most of them employ a higher operating threshold of the differential protection. Besides, some capacitive current compensation algorithms are employed for the phasor based differential protection [6–8]. In this case, the sensitivity and the operation speed will be lowered. Ref. [9] proposed a current differential relay which uses distributed line model to consider line charging current. An adaptive GPS-synchronized protection scheme using Clarke transformation has been proposed in [10]. A transmission line pilot protection scheme based on the individual phase impedance has been proposed in [11]. An adaptive restraint coefficient-based differential protection criterion was introduced [12]. In [13], the dynamic behavior of the power differential relay has been thoroughly investigated.

A new technique for long transmission line protection is put forward. The proposed scheme can distinguish between internal and external faults by comparing the results of the net energy fed into the protected line in a short time interval. The energy is calculated by two different methods. The first method is to calculate the energy flow in the line in a short time interval. The second method is to calculate the energy consumption of distributed elements on the transmission line with the assumption that there is no internal fault on the line. Special means are adopted: 1. use of modal quantities of voltage and current; 2. the instantaneous voltage and current are distributed linearly along the transmission line; 3. the instantaneous voltage and current vary linearly during a sampling interval; and 4. the sampling interval is equal to the travel time of the protected line. The energies of the two methods are equal when there is no internal fault on the transmission line (as proven in Appendix A). The test results show that the proposed technique has highly reliability, fast speed, and excellent performance under high-resistance earth-fault conditions.

This paper is organized as follows: Section 2 enunciates the fundamentals of the proposed scheme. Section 3 presents the algorithms and criteria. Test results are presented in Section 4. Section 5 concludes the paper.

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2. Fundamentals

The new differential protection scheme is initially explained using a single-phase system in this section. Two different methods are applied to calculate the net energy fed into the protected line during a short time interval. In the 1st method, the voltage and current at each end of the transmission line are used to calculate the instantaneous power. The sum of the power at each end is the instantaneous power flow in the transmission line. Then the energy flow in the transmission line (shown in Fig. 1) from time t_1 to t_2 can be obtained by the integral of the instantaneous power over this interval as given below:

$$E_1 = \int_{t_1}^{t_2} [v_M(t) \cdot i_M(t) - v_N(t) \cdot i_N(t)] dt \quad (1)$$

where $v_M(t)$ is the voltage at the relay point M; $i_M(t)$ the current at the relay point M; $v_N(t)$ the voltage at the relay point N and $i_N(t)$ is the current at the relay point N.

This is the first method to calculate the energy flow in a line in a short time interval. The second method is to calculate the energy consumption of distributed elements on the transmission line with the assumption that there is no internal fault on the line, that is

$$E_2 = \int_{t_1}^{t_2} \times \int_0^l \left(i^2(x,t) \cdot R_0 + i(x,t) \cdot \frac{di(x,t)}{dt} \cdot L_0 + v(x,t) \cdot \frac{dv(x,t)}{dt} \cdot C_0 \right) dx dt \quad (2)$$

where x is the distance from the point X to the relay point M; $v(x, t)$ the voltage at point X; $i(x, t)$ the current at point X; l the total length of the line and R_0, L_0 and C_0 is the resistance, inductance and capacitance of the line per unit length.

The energy consumption is the sum of the energy consumed by the resistance, inductance and capacitance of the line. Based on the voltage and current distributions along the line and the instantaneous voltages and currents during the interval, the energy is calculated by integration.

This technique is based on the energy conservation law; "Energy in a system may neither be created nor destroyed, just converted from one form to another". E_1 is compared with E_2. While there is no internal fault on the line, we have $E_1 = E_2$. If there are some differences between the two energies, an internal fault is indicated in the transmission line zone.

3. Energy differential relay

The calculation of the energy fed into the protected line (shown in Fig. 1) required the voltage and current distributions along the line and the instantaneous voltages and currents during the interval. Special means are adopted: 1. use of modal quantities of voltage and current; 2. the instantaneous voltage and current are distributed linearly along the transmission line; 3. the instantaneous voltage and current vary linearly during a sampling interval; 4. the sampling interval is equal to the travel time of the protected line.

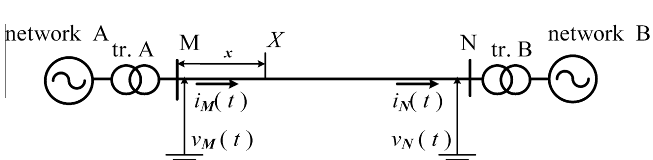

Fig. 1. Circuit diagram of a typical transmission line.

3.1. Algorithm

Assume that the two ends of the protected line are denoted by M and N, the implementation of the protection requires two groups of the space modulus: Modulus 1: v_{MA}–v_{MB}, i_{MA}–i_{MB}, v_{NA}–v_{NB}, i_{NA}–i_{NB}; modulus 2: v_{MA}–v_{MC}, i_{MA}–i_{MC}, v_{NA}–v_{NC}, i_{NA}–i_{NC}. Among which, v_{MA}–v_{MB} represents the voltage difference between phase A and phase B on M side, and i_{NA}–i_{NB} represents the current difference between the phase A and phase B on the N side, and so forth.

Under the assumption that the instantaneous voltage and current are distributed linearly along the transmission line, Eqs. (3) and (4) are derived:

$$v_{m1}(x,t) = v_{Mm1}(t) + \frac{(v_{Nm1}(t) - v_{Mm1}(t))}{l} \cdot x \quad (3)$$

$$i_{m1}(x,t) = i_{Mm1}(t) + \frac{(i_{Nm1}(t) - i_{Mm1}(t))}{l} \cdot x \quad (4)$$

where $v_{m1}(x, t)$ is the voltage of modulus 1 at point X; $v_{Mm1}(t)$ the voltage of modulus 1 on M side; $v_{Nm1}(t)$ the voltage of modulus 1 on N side; $i_{m1}(x, t)$ the current of modulus 1 at point X; $i_{Mm1}(t)$ the current of modulus 1 on M side and $i_{Nm1}(t)$ the current of modulus 1 on N side.

Under the assumption that the instantaneous voltage and current vary linearly during a sampling interval, Eqs. (5)–(8) are derived:

$$v_{Mm1}(t) = v_{Mm1}(k-1) + \frac{v_{Mm1}(k) - v_{Mm1}(k-1)}{\tau} \cdot (t - t_0 - (k-1)\tau) \quad (5)$$

$$v_{Nm1}(t) = v_{Nm1}(k-1) + \frac{v_{Nm1}(k) - v_{Nm1}(k-1)}{\tau} \cdot (t - t_0 - (k-1)\tau) \quad (6)$$

$$i_{Mm1}(t) = i_{Mm1}(k-1) + \frac{i_{Mm1}(k) - i_{Mm1}(k-1)}{\tau} \cdot (t - t_0 - (k-1)\tau) \quad (7)$$

$$i_{Nm1}(t) = i_{Nm1}(k-1) + \frac{i_{Nm1}(k) - i_{Nm1}(k-1)}{\tau} \cdot (t - t_0 - (k-1)\tau) \quad (8)$$

where t_0 is the sampling start time; $v_{Mm1}(k)$, $i_{Mm1}(k)$ the voltage and current sampled value of modulus 1 on M side at sample k; $v_{Nm1}(k)$, $i_{Nm1}(k)$ the voltage and current sampled value of modulus 1 on N side at sample k; $v_{Mm1}(k-1)$, $i_{Mm1}(k-1)$, $v_{Nm1}(k-1)$ and $i_{Nm1}(k-1)$ the voltage and current sampled value of modulus 1 at sample $k-1$ and τ the sampling interval.

The sampling interval is equal to the travel time of the protected line, that is:

$$\tau = l \cdot \sqrt{L_{m1} \cdot C_{m1}} = l \cdot \sqrt{L_{m2} \cdot C_{m2}} \quad (9)$$

where L_{m1}, C_{m1} is the inductance and capacitance of modulus 1 per unit length and L_{m2}, C_{m2} is the inductance and capacitance of modulus 2 per unit length.

Using the 1st method, the energy of modulus 1 flow in the transmission line from time $t_0 + (k-1)\tau$ to $t_0 + k\tau$ can be obtained by the integral of the instantaneous power over this interval between sample $k-1$ and sample k as given below:

$$E_{1m1}(k) = \int_{t_0+(k-1)\tau}^{t_0+k\tau} [v_{Mm1}(t) \cdot i_{Mm1}(t) - v_{Nm1}(t) \cdot i_{Nm1}(t)] dt \quad (10)$$

Using the 2nd method, with the assumption that there is no internal fault on the line, the energy consumption of modulus 1 of the transmission line from time $t_0 + (k-1)\tau$ to $t_0 + k\tau$ can be obtained:

$$E_{2m1}(k) = \int_{t_0+(k-1)\tau}^{t_0+k\tau} \int_0^l \left(i_{m1}^2(x,t) \cdot R_{m1} + i_{m1}(x,t) \cdot \frac{di_{m1}(x,t)}{dt} \cdot L_{m1} + u_{m1}(x,t) \cdot \frac{dv_{m1}(x,t)}{dt} \cdot C_{m1} \right) dx dt \quad (11)$$

where R_{m1} is the resistance of modulus 1 per unit length.