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Intelligent relaying scheme for series-compensated double circuit lines using phase angle of differential impedance

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ABSTRACT

The paper presents a comprehensive intelligent relaying scheme using phase angle of differential impedance (PAODI) for series compensated double circuit transmission lines. The differential impedance (DI) is the ratio of differential voltage phasors of any phase across two ends of the transmission line to the differential current phasors of the same phase of the same transmission line. The PAODI of each phase are used as inputs to the data mining model known as decision tree (DT) to generate final relaying decision to identify the faulty phase(s) involved. The proposed scheme is extensively validated for different fault scenarios including inter-circuit and cross-country faults on the series-compensated parallel transmission developed on Real Time Digital Simulator (RTDS) platform. The test results obtained indicate that the proposed PAODI based intelligent relaying scheme is both dependable and secure in protecting series compensated double circuit transmission lines with a response time of less than 1 and 1/2 cycles.

Introduction

In recent years, because of energy, environmental, and regulatory concerns, the growth of power transmission system has been restricted. Hence, series compensated parallel lines are widely used in modern power system, which offer many advantages, such as increase in power transfer capability, improvement in system stability, reduction in transmission losses and increase in loading capacity of the line [1]. Distance relays are generally used to provide primary and back-up protection to transmission lines. The impedance calculation in case of conventional distance relaying gets affected due to inclusion of the series compensation, and leads to unreliable operation of distance relay. Hence, to switch from protection of an uncompensated transmission line to a transmission line with series compensation is considered to be a difficult task for protection engineers, as it needs to be adapted to the changes introduced by compensation devices. Further, factors like; nonlinear behavior of series capacitor (SC) and metal-oxide varistors (MOVs) during fault, presence of zero sequence mutual coupling between parallel lines etc. makes the conventional distance relaying schemes unreliable for protecting series compensated parallel lines.

The distance relay overreaches if series capacitor (SC) is included in the fault circuit. The modification in the relay settings is advisable to accommodate the series compensation, only when the capacitor becomes part of the faulted circuit for a fault including compensator [2]. However, over-voltage protection of the SC could bypass the capacitor from the faulted circuit. Generally, a Spark Gap (SG) or Metal Oxide Varistor (MOV) or both, with a bypass circuit breaker, protect the capacitor against over-voltage. This results in to two different impedances as follows. For the faults involving higher amplitude of current, voltage across the capacitor increases to a truly high value, which triggers MOV conduction to bypass the capacitor. In this case, the impedance for combination of SC–MOV will reduce to the impedance offered by MOV only. However, for faults involving lower amplitude of current, the MOV remains in its high impedance state. The SC–MOV combination offers impedance equal to parallel combination of the pair. Thus, two impedance conditions bring difficulty in relay setting. Further, the occurrence of inter-circuit and cross-country faults on a double circuit line can cause serious system instability [2,3]. The probability of occurrences of these types of fault is high due to lightning stroke, catastrophic accident or bush fires under transmission lines which results in unusual voltage and current distributions. In such situation, the fault impedance calculation performed by the conventional distance relaying is incorrect. Again, zero sequence mutual coupling causes error in direction and distance estimations for a double circuit line [3]. The problem is compounded by the degree of compensation of the transmission lines leading to unreliable performance of the distance relay [4].

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These protection issues can be addressed either through the development of dedicated relaying schemes [5] or through the adaptive protection for the conventional distance relays [6]. The development of dedicated schemes has attracted much more attention as compared to the adaptive trip boundary protection. In [7,8], research works have been carried out on ground fault analysis for single circuit series compensated transmission lines. Some of the researchers have presented solutions to the problems of mutual coupling present between double-circuit lines along with the effect of fault resistance [9,10]. However, the effect of series compensation has not been considered. Adaptive distance relaying for series compensated parallel lines during inter circuit faults has been suggested in [11,12] without considering the security aspect of the scheme. Further, adaptive change of relay trip boundary in real time environment is less dependable as compared to dedicated relaying schemes. In [13] a cross differential protection scheme in presence of STATCOM has been suggested for parallel lines, but the scheme will not work if one of the circuits is out of service. Also issues like cross-country faults, inter-circuit faults and effect of power swing have not been addressed. Recently, a directional relaying scheme is presented for series compensated double circuit lines [14]. However, the investigation does not discuss about the selectivity and security aspect of the scheme. Also, it has not included the effects of power swing and faults during power swings on the relaying scheme.

Looking at the aforementioned protection challenges faced by the existing protection schemes, there is a strong motivation in developing a new comprehensive intelligent relaying scheme for series compensated parallel transmission lines. The proposed intelligent relaying scheme uses the differential signal called PAODI, which is derived from the voltage and current phasors at both ends of the transmission line [15]. PAODI of each phase is further processed through the data mining model known as decision tree (DT) [16] for generating intelligent relaying decision. The relaying scheme is extensively tested for faulted compensated parallel transmission lines on RTDS platform which uses parallel processing techniques (PB5 card) on rack-mounted processors to maintain continuous real-time digital simulation of a power system of arbitrary complexity. This paper is organized as follows: Section 'Concept of PAODI' describes the principle of PAODI based protection, Section 'System studied on RTDS platform' explains the system under study, Section 'Performance assessment and discussion' shows the results obtained from the simulation studies and Conclusions of the study are presented in Section 'Conclusions'.

Concept of PAODI

The proposed relaying scheme is developed using a new differential signal named as "PAODI". Further, a "PAODI domain" is recognized, which decides the operating and restraining zones of the proposed intelligent relaying scheme. Initially, the concept of PAODI and its domain is explained for a single circuit transmission line. The following parameters are considered for deriving expression for PAODI:

E_s, E_r: Voltages of sources at sending end and receiving end of the transmission line, respectively.
$\overline{V}_s$, $\overline{V}_r$, $\overline{I}_s$, $\overline{I}_r$: Voltage and current phasors measured at the sending end bus and receiving end bus, respectively.
$\overline{V}_{sc}$: Voltage drops while across the series capacitor.
$\overline{I}_{sg}$, $\overline{I}_{rg}$: Currents through the equivalent capacitance at sending end(s) and receiving end(r), respectively.
$\overline{I}_f$: Current through the fault branch with fault resistance of R_f.
Z_s, Z_r: Equivalent impedance of power source at sending end and receiving end.
Z_{sg} (=2/Y), Z_{rg}(=2/Y): equivalent lumped capacitive impedances of the line.
Z_{ls}: Line impedance from sending end to the point F.
Z_{lr}: Line impedance from receiving end to the fault point F.
Z_l: Entire line impedance.
Z_{sc}: Impedance offered by series capacitor.
Transmission line: π-equivalent circuit.

Mathematically PAODI is defined as follows:

$$\mathrm{PAODI} = \arg(\mathrm{DI}) \tag{1}$$

$$\text{where } \mathrm{DI} = \left(\frac{\Delta\overline{V}}{\Delta\overline{I}}\right) = \left(\frac{\overline{V}_s + \overline{V}_r}{\overline{I}_s + \overline{I}_r}\right) \tag{2}$$

$$\mathrm{PAODI} = \arg\left(\frac{\overline{V}_s + \overline{V}_r}{\overline{I}_s + \overline{I}_r}\right) \tag{3}$$

A. Characteristics of PAODI for external faults in case of series compensated lines

Series compensation at the middle of the line

Any fault occurring outside the zone of protection is called external fault. When an external fault occurs, the differential current ($\Delta\overline{I}$) constitutes the capacitive current. Fig. 1 shows the system equivalent circuit in case of external faults. The differential current of the line during external fault is:

$$\Delta\overline{I} = \overline{I}_s + \overline{I}_r = \overline{I}_{sg} + \overline{I}_{rg} = (\overline{V}_s/Z_{sg}) + (\overline{V}_r/Z_{rg}) \tag{4}$$

where $Z_{sg} = Z_{rg} = 2/Y$

$$\Rightarrow \mathrm{DI} = \frac{(\overline{V}_s + \overline{V}_r)}{\Delta\overline{I}} = \frac{(\overline{V}_s + \overline{V}_r)}{(\overline{V}_s/Z_{sg}) + (\overline{V}_r/Z_{rg})} = 2/Y$$

$$\Rightarrow \mathrm{PAODI} = \arg(\mathrm{DI}) \quad [\text{Higher absolute value with negative sign}] \tag{5}$$

Half series compensation at both ends of the line

The equivalent circuit of the system with half series compensation at both ends of the line is shown in Fig. 2. $\overline{V}_{sc}$ is the voltage drops while across the series capacitor and $\overline{I}_s$ and $\overline{I}_r$ are the current flowing through the series capacitor at both end of the transmission line. Assuming level of compensation of series capacitor to be 50%,

$$Z_{sc} = -0.5Z_l$$

$$\overline{V}_{sc} = Z_{sc}/2 \times \overline{I}_s = Z_{sc}/2 \times \overline{I}_r = -0.25Z_l \times \overline{I}_s = -0.25Z_l \times \overline{I}_r$$

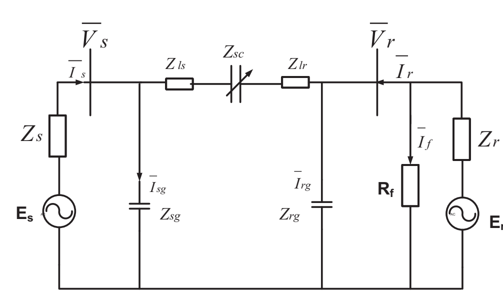

Fig. 1. Equivalent circuit for an external fault when series capacitor is at the middle.