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Fault location on series and shunt compensated lines using unsynchronized measurements

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ABSTRACT

This paper proposes a simple, accurate and non-iterative fault location scheme for series and shunt compensated transmission lines. The proposed algorithm utilizes unsynchronized measurements from the two ends of a transmission line and the monitoring system if a fixed series compensation (FSC) device is installed. Data synchronization is carried out using post-fault data samples to increase the accuracy. The proposed algorithm is independent of the reference bus selection and is extensively tested for all major fault types and fault resistance variations. The results prove that the proposed algorithm yields accurate estimate of fault location.

1. Introduction

The protection of series-compensated transmission lines is one of the most challenging tasks for protection engineers [1–12,20]. Series-compensated transmission lines are widely used in modern power systems for several advantages, including system stability improvement, bulk power transfer increase, and voltage control enhancement. Despite the obvious advantage of using series compensation, series capacitors (SC) are generally known to cause an increase in the fault current level due to the reduced line reactance [12]. Additionally, series capacitors may cause sub-synchronous resonance. Conventional fixed series compensation (FSC) devices also incorporate a single air-gap overvoltage protection scheme where the flash-over of the gap results in the sudden removal of the SC from the system. The sudden removal and insertion of the SC may cause voltage and/or current inversion. This phenomenon leads to loss of directionality in directional protective devices [13].

Distance relays, which basically estimate the impedance to the fault point, are influenced by the series compensation. Series compensation affects the impedance estimation to the fault in an unpredictable manner. For faults near the SC, the impedance between the relay location and the fault point is capacitive rather than inductive. Relays installed on the fault side of the transmission line might be able to detect the fault successfully but not the relays on the adjacent side of the SC. Therefore, careful consideration is required to mitigate the adverse effects of compensating elements.

Fault location on power transmission lines remains the focus of active research and a theme that is closely associated with the application of distance relays [14,15]. Fault location schemes for series-compensated transmission lines can be broadly categorized into two types: Traveling-wave based fault location algorithms [16,17] and fundamental frequency based (impedance principle) fault location schemes. The latter can be sub-classified based on synchronized measurements [2,3,6] or asynchronous measurements acquired from one or both ends of a transmission line [4,5,7,8,12,21].

Metal Oxide Varistors (MOV) are non-linear conduction devices that are installed across series capacitors to provide overvoltage protection. The conduction through the MOV remains mute during the normal operation of the power system. When a fault occurs, the fault current leads to an increase in the capacitor voltage and the MOV starts to conduct once the voltage exceeds the threshold [12,13]. The complexity of fault locating algorithms reported in literature is due to the fact that the current-dependent impedance of the SC/MOV device cannot be pre-determined and has to be estimated. A sizeable portion of the computational effort in [1–3,7] is dedicated to estimate the behavior of the compensation device when the series capacitor and the

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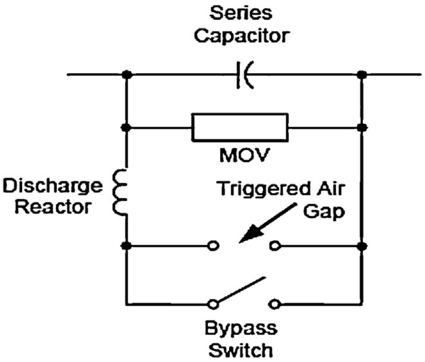

Fig. 1. Generalized SC/MOV model.

MOV are partially conducting. A fault locating algorithm, which estimates the voltage drop across the SC and MOV using the on-line solution of non-linear differential equations, is proposed in [15].

In this paper, the solution to the transmission line protection problem is modeled as a fault locating algorithm. The traditional method of approximating the series capacitor voltage from the relay line terminal is abandoned in favor of the state-of-the-art FSC monitoring systems that can accurately measure three-phase currents and voltages. A Fault locating algorithm, for both series and shunt compensated transmission lines, using unsynchronized two-ended measurements is proposed. The data synchronization is achieved using post-fault data samples to enhance the performance of the algorithm. The fault locating algorithm simultaneously processes the positive and negative sequence fault impedance loops for unsymmetrical faults, whereas positive and superimposed positive sequence fault impedance loops are utilized for symmetrical faults.

The rest of the paper is organized as follows. Section 2 describes the derivation of the fault location and data synchronization procedure and Section 3 clearly demonstrates the performance of the proposed algorithm. Section 4 concludes the paper.

2. Fault locating algorithm

2.1. Fault location for series compensated lines

A typical fixed series compensation (FSC) device, along with the associated nonlinear overvoltage protection (MOV), has three well-known modes of operation [1,3]:

- Large fault current mode,
- Low fault current mode, and
- Intermediate fault current mode.

The algorithms presented in literature would do well if a dedicated procedure existed to remove the dependency on FSC/MOV mode of operation. This would help spare the burgeoning computational effort and improve the accuracy of the fault locating procedure. A generalized model of the SC/MOV device is shown in Fig. 1. The v–i characteristic of the non-linear MOV is often approximated by an exponential function as:

$$i_{\mathrm{MOV}} = P\left(\frac{v_x}{V_{\mathrm{REF}}}\right)^q \tag{1}$$

where i_{MOV} and v_x are the MOV current and voltage respectively, P and V_{REF} are reference constants and q is the exponent of the characteristic. A lot of effort is directed in the literature toward the calculation of the series capacitor voltage using the exponential model given in (1), which requires extensive calculations to get accurate results. Approximations of the capacitor voltage can still have considerable error when the FSC bank is not close to the relay. This is because the current flowing through the FSC device is different from what is measured at the line terminal due to the charging current [18]. The proposed method utilizes accurate three-phase current and voltage measurements from the FSC monitoring system.

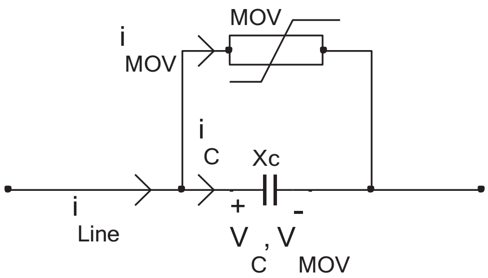

Fig. 2. SC/MOV bank structure.

2.1.1. Fixed series compensation monitoring system

Fixed series compensation monitoring systems are expressly designed to gather real-time information on the physical state of FSC devices and have integrated communication capabilities. The use of FSC monitoring system has been a growing trend since the 1980s to allow for programmed maintenance. They also help to avoid unnecessary interruptions in bulk power transfer. A typical FSC monitoring system consists of a data acquisition unit and several other protection, control and supervision systems (PCSS) [18,19]. The data acquisition unit of the monitoring system gathers and transmits data for transmission line current, capacitor bank and MOV leakage current and phase voltages of the FSC device.

The MOV element essentially operates in an open-circuit condition as long as the MOV voltage remains below the threshold. Since the series capacitor and MOV leakage current measurements are available through the monitoring system, the phase voltages of the series capacitor can be calculated by the onboard processing units [18].

With reference to the SC/MOV bank structure in Fig. 2, the capacitor voltage is given by:

$$v_C(t) = \frac{1}{C}\int_{t_0}^{t} i_C(t)dt + v_C(t_0) \tag{2}$$

where,

$$i_C(t) = i_{\mathrm{Line}}(t) - i_{\mathrm{MOV}}(t) \tag{3}$$

The discrete-time solution to the continuous-time differential equation is given by:

$$v_C(n) = \frac{T_s}{2C}(i_C(n) + i_C(n-1)) + v_C(n-1) \tag{4}$$

where,

$$i_C(n) = i_{\mathrm{Line}}(n) - i_{\mathrm{MOV}}(n) \tag{5}$$

The FSC monitoring system can provide accurate phase voltage and current measurements in real-time and will be used for the fault locating algorithm proposed in this section. The synchronization between the data measured at the FSC unit and the primary reference bus cannot be guaranteed and is taken into account by the fault locating procedure.

2.1.2. Data synchronization and fault locating scheme

The algorithm proposed in this paper uses unsynchronized measurements from the two ends of the transmission line and the FSC unit. The algorithm is designed to work for all fault types and fault