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An algorithm based on traveling waves for transmission line protection in a TCSC environment

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ABSTRACT

This paper describes a new relaying algorithm for the protection of transmission lines with a Thyristor Controlled Series Compensator (TCSC). The algorithm is based on the pattern of traveling waves generated during a fault event. Several tools like modal analysis, the discrete wavelet transform and a probabilistic neural network trained to work with the energy contained in the wavelet transform coefficients are applied to analyze the high frequency pattern generated during the fault. The proposed algorithm is capable of detecting, locating and classifying faults in a reliable way. The impact of harmonic frequencies generated by the TCSC in the protection algorithm was also analyzed. Several studies were carried out in order to validate and to assess the effect of several fault parameters on the algorithm accuracy. The obtained results show that for a sampling rate of 100 kHz, the algorithm error in calculating the distance to the fault is less than one percent of the total transmission line length. A higher sampling rate improves the algorithm accuracy.

Introduction

In the last decade, power electronics devices have been increasingly incorporated on electrical power systems providing greater flexibility and controllability. In the near future it is expected a large scale integration of these devices on electrical networks under the smart grid concept.

Power electronic controllers for Flexible AC Transmission Systems (FACTS) are still a topic of concern for the industry because of its dynamic interaction with other power systems components. In the protective relaying area there are still some challenges to undertake. A particular case of concern is the performance of protection schemes for long transmission lines compensated with power electronic devices like the Thyristor Controlled Series Compensator (TCSC), the Static Synchronous Series Compensator (SSSC) and the Static Var Compensator (SVC). In the above cases, distance relays may fail to detect and locate faults along the transmission line when these devices are connected to the electrical power network. This is explained by the unconventional behavior of the impedance seen by the relay, which is dependent on the fault and power electronic device locations [1–3].

In order to overcome this limitation, some alternative protection schemes and algorithms for transmission lines with FACTS controllers have been proposed. In 2002, Chi-Shan et al. developed a new scheme based on Phasor Measurement Units (PMU) for calculating the distance to the fault by using the voltage drops measured on different buses [4]. In 2004, Dash and Samantaray proposed an algorithm capable of detecting whether the fault is located before or after the TCSC by taking into account the higher components in the frequency spectrum [5]. In 2005, Sidhu and Khederzadesh developed a new technique based in the modified apparent impedance seen by the relay. This approach requires synchronized measurements from both line ends [6]. In 2007, Dash et al. used the 3rd and 5th harmonics generated by the TCSC and a Vector Machine Support (VMS) technique to locate and classify faults on series compensated transmission lines using FACTS controllers [7]. In 2011, El-Zonkoly and Desouky used a wavelet entropy (WE) technique applied to voltages and currents measured by the relay in order to detect faults on transmission lines compensated with the SSSC [8]. This algorithm is based on detecting changes in magnitude and frequency in the measured signals due to transmission line faults. Also in 2011, Ahsaee and Sadeh used measurements in both line ends and calculated the distance to the fault by considering the speed of propagation of electromagnetic waves [9]. This approach also incorporates an optimization method in order to identify the faulted line section.

It should be mentioned that these algorithms are based on a half cycle window [7,8], three cycle window [4] and the remaining contributions do not specify window length [5,9]. For protective

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relaying these are long periods of time and therefore they cannot be considered like high speed protection schemes. In addition, some techniques [4,6,9] are based on synchronized measurements at both line ends.

Traveling wave techniques have been used for a long time to detect and locate faults in AC [10–12] and HVDC [13,14] transmission lines. In general, they have faster operating times than conventional impedance based schemes [15]. However, its application in a FACTS environment is not an easy task. First, it is required to analyze and assess the impact of harmonic frequencies generated by FACTS controllers on the traveling waves. This is because harmonics can distort or modify the high frequency pattern of reflections and refractions used by traveling wave relays during a fault event. The interaction between harmonic frequencies and traveling waves can be analyzed by using the Discrete Wavelet Transform (DWT), which is a powerful tool for detecting transient events on transmission lines, given its ability for discriminating high from low frequencies during a given fault event [16]. This DWT capability is very helpful and facilitates the development of algorithms for high speed protective relaying.

The aim of this paper is twofold: first, to analyze the interaction between traveling waves generated by faults and the harmonic frequencies produced by the TCSC. This analysis laid the foundations for the second objective, which is the development of a new algorithm for high speed protection based on traveling waves, the DWT and a probabilistic neural network (PNN). The algorithm must be capable of fault detection, location and classification on long transmission lines compensated with a TCSC. Several cases of study are presented which will demonstrate the effectiveness of the proposed algorithm. Also, an assessment about the effect of several line and fault parameters on the algorithm accuracy is included.

The paper is organized as follows: first, the interaction between harmonic frequencies generated by the TCSC and the traveling wave pattern produced during a fault event is analyzed. Second, the proposed protection algorithm is developed using modal analysis, the DWT and a PNN. Then, the proposed algorithm is validated and several studies on transmission lines faults involving the TCSC are presented. Finally the conclusions are given.

Traveling waves and the TCSC

The first step in the development of the proposed algorithm is to assess the interaction between harmonic frequencies generated by the TCSC and the traveling waves seen by relays during a fault event. Let us consider a transmission line with a TCSC, as shown in Fig. 1. It is well know that after a fault event two traveling waves are propagated in opposite directions along the transmission line. In general, the voltage at any point "x" along the transmission line is given by [17]:

$$V_x = (V_- e^{-\gamma x} + V_+ e^{+\gamma x}) \tag{1}$$

where γ is the transmission line propagation coefficient, $V_- e^{-\gamma x}$ represents a voltage incident wave and $V_+ e^{+\gamma x}$ is a voltage reflected wave from the remote end.

From Fig. 1, for a fault between the local end and the TCSC, case 1, traveling waves arrive practically undisturbed to the relay (R) in the local end. This particular case does not possess any serious difficulty for conventional traveling wave relays. However, if the fault occurs between the TCSC and the remote end, case 2, traveling waves see a change of impedance at the TCSC terminals before arriving to relay (R). This fact may distort and modify the traveling waves arriving to the local end. The reflection coefficient at the transition point is [17]:

$$\rho_v = \frac{V_+ e^{+\gamma x}}{V_- e^{-\gamma x}} = \frac{Z_x - Z_0}{Z_x + Z_0} \tag{2}$$

where Z_x is the TCSC impedance and Z_0 is the transmission line characteristic impedance. The reflection and refraction coefficient can be used to analyze how the TCSC modify the traveling wave characteristics arriving to the relay (R) in the local end during a fault event. This is described in the following sections.

TCSC performance at low and high frequencies

Table 1 shows the relevant electrical parameters for the TCSC depicted in Fig. 1. These parameters are selected in order to provide 70% series compensation for a 345 kV transmission line whose electrical parameters are given in Ref. [18]. Traveling waves produced during fault events between the TCSC and the remote end reach the TCSC terminals when the thyristors are in open or closed state. The circuit for both cases is shown in Fig. 2(a) and (b), respectively. On the other hand, Fig 2(c) shows the voltage across the capacitor C_{TCSC} (V_{TCSC}) and the current through the parallel inductance L_{TCSC} (I_L) during TCSC normal operating conditions and a firing angle $\alpha = 160°$. For understanding the interaction between traveling waves and the TCSC both cases, open and closed, need to be considered.

For Fig. 2(a), when the thyristors are in open state, $0 \leqslant t \leqslant \alpha$, the high frequency impedance seen by the traveling waves is [17]:

$$Z_x(s) = Z_0 + \frac{1}{s\frac{(C_{TCSC})(C_F)}{C_{TCSC}+C_F}} \tag{3}$$

By substitution of (3) in (2), the reflection coefficient ρ_v is:

$$\rho_v = \frac{1}{2Z_0 C_E s + 1} \tag{4}$$

where C_E is the equivalent for C_{TCSC} and C_F and s is the Laplace transform variable. By transforming ρ_v to the time domain:

$$\rho_v(t) = \exp^{(-\tau t)} = \exp^{(-2Z_0 C_E t)} \tag{5}$$

For the electrical parameter shown in Table 1, the time constant for the circuit is τ = 45 ms. This means that traveling waves are reduced to about one third of its original magnitude after a time constant. This period of time is too long to have any significant impact on traveling wave magnitudes used by a high speed relaying application. Hence, when the thyristors are in open state traveling waves get through the TCSC with basically no attenuation.

For Fig 2(b), when the thyristors are in closed state, $\alpha \leqslant t \leqslant \sigma$, the TCSC performance is quite similar to the previous case. The high frequency impedance seen by the traveling waves arriving to terminals is:

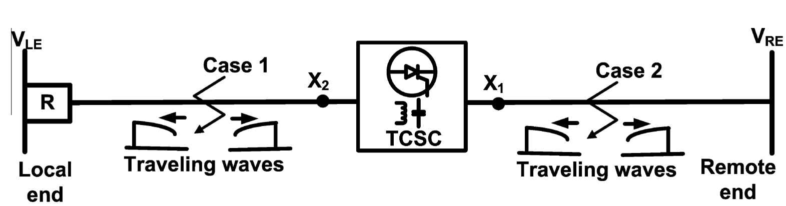

Fig. 1. Traveling waves during two fault events.