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Enhanced performance for distance relays due to series capacitors in transmission lines

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ABSTRACT

This paper presents the Prony method as a filtering technique and its implementation in distance relay algorithms. First, the distance relay model and the impact of non-filtered frequency components when using typical digital filters in the operation of the distance relay are presented. Next, an overview of transmission line series compensation and its effects in distance relay estimation during the fault period are evaluated. Then, we present a solution using Prony method as filtering technique in distance relay algorithms. Next, the proposed algorithm is evaluated in reach and operation time of the relay, and a 3D characteristic of the Mho distance relay is presented in the impedance plane to evaluate the proposed algorithm. The proposed filter is implemented as a solution to the distance relay estimation error in the apparent impedance measurement. Lastly, an actual fault event is evaluated to validate the proposed distance relay algorithm.

1. Introduction

The necessity for long distance transmission of electric power has grown rapidly during recent years. Line reactance becomes an increasingly important problem as transmission distances continue to increase. Long lines cannot be loaded sufficiently for maximum overall economy due to the limitations imposed by transient stability and kilovar requirements [1]. The most important alternative to reduce the equivalent line impedance by increasing the transmission voltage is the use of line reactance compensation. Such compensation can be best obtained through the use of capacitors operating in series with the line conductors [1–3].

The capacitor banks are used for series compensation, improve the voltage profile and optimize the current flow between transmission lines connected in parallel. Moreover, it is very difficult to measure the fundamental components of the voltage and current signals when line series compensation is used because the system becomes a resonant RLC (Resistance–Inductance–Capacitance) circuit [3–6]. Additionally, there are problems determining whether the series compensation is within the fault loop during phase to ground faults, causing overreach in the distance relay and, as a consequence, a fault detection problem.

There are solutions in distance protection algorithms for error compensation due to overreach protection [7,8]. However, these solutions do not completely compensate for the error because, when a low magnitude fault current occurs near the series capacitor, this capacitor will remain connected to the line, causing the relay to see the fault backwards [7,9,10]. Moreover, due to the characteristics of the line with series compensation (series or parallel resonant circuit), there are low frequency components in voltage and current signals (subharmonics) that appear during a fault in the transmission line [20]. Frequency components such as interharmonics or subharmonics in the voltage and current signals (electric input signals of the distance relay) cause an error in the fundamental frequency phasor estimates of voltage and current required by the distance relay [11]. This is because the conventional digital filters, such as Cosine and Fourier filters, have a frequency response that cannot reject these frequency components [11]. The main purpose of the conventional digital filters in distance relays is to estimate the fundamental frequency phasor of the electric input signals required by the relay. However, when frequency components such as interharmonics or subharmonics exist in the voltage and current signals, the conventional Cosine or Fourier digital filters will cause an error in the fundamental frequency phasor estimate. Therefore, an error will result in the estimate of apparent impedance. This will compromise the performance of the distance relay, causing under-reach or overreach (fault detection problems).

The Prony method is a good alternative to obtain the correct apparent impedance measurement by estimating the fundamental voltage and current frequency phasors [11,12]. The main focus of the analysis presented in this paper is to obtain a better estimate of fundamental frequency phasors of voltage and current signals by using the Prony method in the distance relay algorithm.

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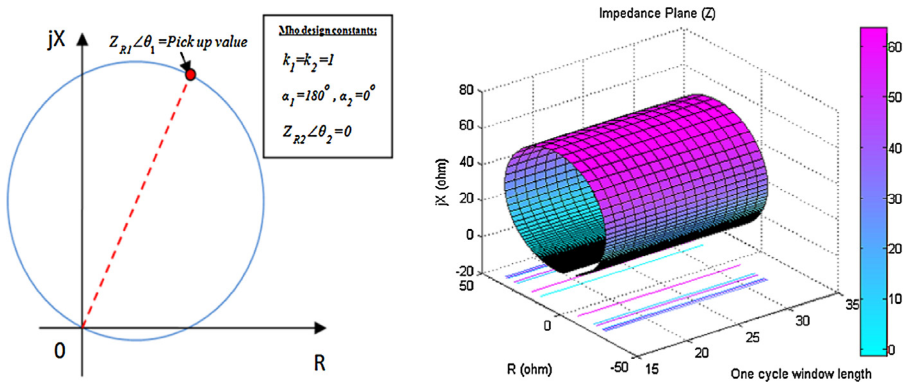

Fig. 1. Mho operation characteristic (fundamental frequency).

2. Distance relay model

The distance relay operation determines the trip condition based on the phase comparison between operation and polarization input signals.

Distance relay models have a phase comparator that responds to the phase angle displacement between input signals [13]. The input signals of the phase comparator are obtained using the design constants and the electric signals measured using the instrument transformers. The model of the distance relay is presented in (1).

$$S_1 = k_1\angle\alpha_1 \cdot V_r\angle 0^o + Z_{R1}\angle\theta_1 \cdot I_r\angle - \varphi_r$$
$$S_2 = k_2\angle\alpha_2 \cdot V_r\angle 0^o + Z_{R2}\angle\theta_2 \cdot I_r\angle - \varphi_r \quad (1)$$

where S_1 and S_2 are the input signals that establish the trip signal; $\bar{k}_1$ and $\bar{k}_2$ are the design constants; $\bar{Z}_{R1}$ is the replica impedance of the protected transmission line; and $\bar{Z}_{R2}$ is an impedance value which is multiplied by the current $\bar{I}_r$, and it will result in a polarization voltage; and $\bar{I}_r$ and $\bar{V}_r$ are the electric input signals, which are estimated by the phasor estimation technique (Fourier filter or Cosine filter) to obtain the fundamental frequency phasor [11,14].

The phase relays are required for the detection of phase-to-phase faults; an important aspect in the distance relay design is that the correct values of $\bar{I}_r$ and $\bar{V}_r$ must be selected and the typical sampling time used for the electric input signals is 16–32 samples per cycle [11,15]. In Table 1, the electric input signals that correspond to the phase distance relay units are presented.

In Fig. 1, the Mho operation characteristic is presented in the tridimensional space of the impedance plane through time; the time is represented by the one cycle window length displacement. The estimated fundamental voltage and current phasors are used for the relay (phase relay unit). The input signals V_r and I_r, are used (see Table 1) to form the operation characteristic and the phase comparator scheme. In this study, the Mho characteristic is evaluated; however, the methodology is valid for other distance relays characteristics.

It is necessary to incorporate two stages of filtering to eliminate undesired frequency components, such as noise, harmonics and the DC component because these frequency components are considered to be a source of error that could affect the selectivity of the relay (see Fig. 2).

Table 1
Electric input signals for distance relay unit.

Unit	Voltage (V_r)	Current (I_r)
Phase		
(AB)	$V_{an} - V_{bn}$	$I_a - I_b$
(BC)	$V_{bn} - V_{cn}$	$I_b - I_c$
(CA)	$V_{cn} - V_{an}$	$I_c - I_a$

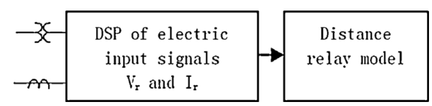

Fig. 2. Distance relay structure for input signal processing.

There are two filter stages, analog and digital; these are intended to reduce the operation time in fault detection. Generally, the analog filter used is a Butterworth filter of 2nd or 4th order with a cutoff frequency of 360 Hz (see Fig. 3); this filter is preferred given that it has a flat response in the passband and decreases monotonically in the stopband [16].

After the analog filter stage, the signal is digitalized, and the increment in the sampling frequency allows for a substantial increment in the signal resolution. However, the microprocessor burden is increased. A reduction in the "aliasing" effect is obtained by tuning between the analog and digital filters. By allowing for an overlap of the filter frequencies, it is possible to remove the analog filter by oversampling of the signal.

The digital filtering is performed with FIR (*Finite Impulse Response*) filters. Because there is no recursion, i.e., the output depends only on the input and not on past values of the output, the previous signal conditions do not influence the distance relay fault condition. Also, the IIR (*Infinite Impulse Response*) filter generally produces a phase angle distortion, which is opposite to FIR filter behavior. This condition allows for natural zeros in the harmonic frequencies of the frequency response, which, in turn, allows for a rejection of the frequency components (see Fig. 3).

The distance relay algorithms used for the fundamental frequency component estimation of voltage and current phasors use the Fourier or Cosine filter (see Fig. 3). In studies where the digital filters are evaluated [17] in the fundamental frequency phasor estimation, the Cosine filter showed good results in the rejection of the DC component during the fault period [17].

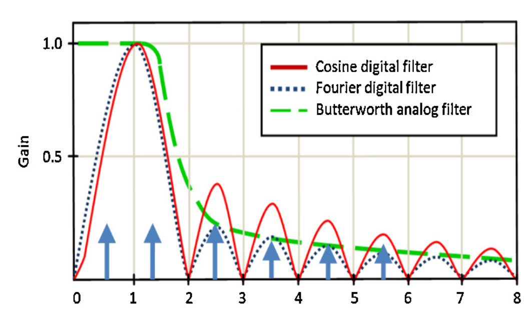

Fig. 3. Analog and digital filter frequency responses in distance relays.