Electric Power Systems Research 162 (2018) 142–149

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Influence of instrument transformers and anti-aliasing filters on the performance of fault locators

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ARTICLE INFO

Keywords:
Anti-aliasing filters
Impedance-based fault locators
Instrument transformers
Transmission lines
Traveling wave-based techniques

ABSTRACT

Anti-aliasing filters are used in cascade with instrument transformers (IT) as part of protective relay data acquisition systems for providing input signals to fault locators. Due to IT and anti-aliasing filters transient responses, the fault locators input data may not be replicas of the power network voltage and current waveforms, and incorrect information may be transferred to protection devices. In this paper, the performance of traveling wave-based and impedance-based fault location techniques are evaluated by extensive short-circuit simulations considering different IT topologies and anti-aliasing filters. The total amount of fault location estimated errors were combined to generate an error function and an original study about a thorough statistical analysis was performed. From the obtained results, the errors can be approximated by a function with normal probability distribution, and the fault location performances are directly affected by the fault-induced amplification and attenuation of the highest frequencies at the IT spectrum and the oscillations presented in the anti-aliasing filters bandpass.

1. Introduction

When a fault occurs on a transmission line, it is important for a utility to accurately locate the fault as quickly as possible in order to minimize potential damages that may take place in the power network, maintaining the system reliability and stability. The faulty section of the electric power system is disconnected through trip signals provided by protective relaying devices, in which fault location algorithms are generally embedded. If the performance of the protective device is not fast and accurate enough, prolonged outages may occur and utility's service reliability may be questioned [1]. However, the accuracy of fault locators may be affected when the line protection trips before instrument transformers (IT)-induced transients are completely damped. This context highlighted the importance of fault location studies and it has attracted the attention of electric power system researchers worldwide.

The fault location procedures are generally classified into impedance-based, traveling wave-based, high frequency components, and knowledge-based techniques [1]. Regardless of the used category, the fault location algorithms process voltage and/or current signals taken from IT, as coupling capacitor voltage transformers (CCVT) and current transformers (CT), respectively. The IT are crucial input sources of voltage and current measurements to protective devices since they provide a cost-efficient way of obtaining scaled-down replicas of power system electrical quantities [1–4]. Even though instrument transformers provide good accuracy for voltage and current signals during power system steady-state operation, the electromagnetic coupling presented at the IT primary and secondary sides may insert some signal deviations during faults, which in turn may affect the protection schemes and the fault locators performances [3–6].

The IT secondary voltage and current waveforms must be sampled by analog-to-digital (A/D) converters prior to be processed by fault location algorithms. However, the obtained digital information taken from the A/D output only presents a frequency equals to the analog frequency if the continuous signal is sampled at a sampling rate (f_s) of at least twice its maximum frequency component (f). Sampling an analog waveform with a frequency lower than $2f$ may result in a set of samples different from the A/D input, assuming a frequency and phase change effects on the sampled signal (aliasing phenomenon). In this way, analog low-pass anti-aliasing filters are usually applied to prevent the aliasing occurrence during sampling procedures [1]. A second or third order Chebyshev, Butterworth or Bessel filters may be used to satisfy protection requirements [2]. Nevertheless, these types of filters may also insert some deviation on the measured voltage and current signals due to their frequency and dynamic responses, which must be taken into account during power system protection and fault location studies.

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https://doi.org/10.1016/j.epsr.2018.05.016
Received 15 December 2017; Received in revised form 15 May 2018; Accepted 16 May 2018

The impact of IT-induced transients during short-circuits on the performance of protection [3,4,7,8] and fault locators [1,5] is well reported. However, investigations concerning the transient behavior of different types of anti-aliasing filters in cascade with IT are rarely reported in literature and still demand more attention. The work performed here is part of the brazilian research project ANEEL 0048-2011023/2012, CTNI 92.2012.5240.00. It is an extension of the work done in [6], where the influence of IT and anti-aliasing filters were taken into account in relation to some impedance-based and traveling wave-based fault location techniques, but the obtained results were not investigated in detail about the transient interaction between the IT and power grid as well as the cause of some outliers that affect the fault locators performances. In this way, this paper addresses a thorough analysis about the impact of IT in cascade with different anti-aliasing filters on some fault location routines, and an original detailed statistical study is performed in relation to the errors obtained by the fault locators.

The evaluations of the IT-induced transients in cascade with some anti-aliasing filters on impedance-based and traveling wave-based fault locators are performed through extensive short-circuit simulations using the Alternative Transients Program (ATP) [9]. In each simulation, the fault variables are varied (location, type, resistance and inception angle) and the error is estimated considering ideal measurements (primary voltage and/or current signals), secondary signals and filtered secondary waveforms as input data to the algorithms.

2. Anti-aliasing filters

The sampling theorem indicates that a continuous signal can only be properly sampled if its highest frequency components are not above one-half of the sampling rate (Nyquist frequency) [1,2]. In cases of faults in transmission lines, high frequency fault transients can be induced in voltage and current signals due to abrupt changes at power network electrical quantities and electromagnetic coupling between the IT primary and secondary sides. In these cases, since the protective relays usually present a fixed sampling frequency, the sampled information output may be different from the one at its input. This aliasing situation is illustrated in Fig. 1, in which two signals (S_1 and S_2) are sampled at f_s = 960 Hz. The S_1 and S_2 frequencies are f_1 = 120 Hz and f_2 = 840 Hz, respectively.

As shown in Fig. 1, sampling S_2 at 960 Hz results in obtaining digital information completely different from the original signal. In addition to it, there is a phase change by π. This aliasing phenomenon occurs because f_2 is higher than the Nyquist threshold. On the other hand, the S_1 signal is properly sampled at f_s and may be correctly used as input data for computer relaying applications. In this way, the possibility to properly perform the sampling process consists on removing frequencies higher than the Nyquist threshold from the A/D converter input. This is obtained by applying an analog low-pass filter (anti-aliasing filter) with a cut-off frequency (f_c) of at most the Nyquist frequency prior to sampling [2]. To illustrate this situation, considering that frequencies at the order of f_2 are superimposed in a voltage or current signal as in the case of S_2, a second order Butterworth filter with f_c = 480 Hz was applied prior to sampling S_2, resulting in the S_3 sampled signal shown in Fig. 1. It is noticeable that S_2 was quite attenuated by the filter, preventing the aliasing occurrence and its transfer to fault locators.

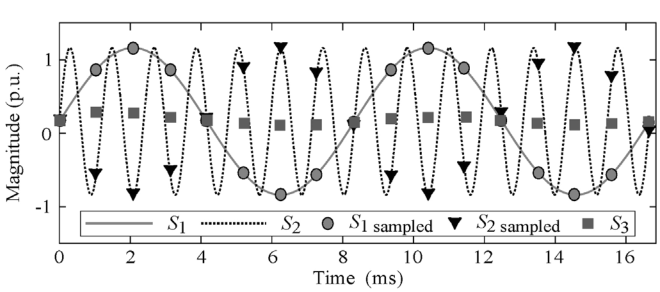

Fig. 1. Example of sampling S_1 (f_1 = 120 Hz) and S_2 (f_2 = 840 Hz) signals with a sampling rate of f_s = 960 Hz.

An ideal anti-aliasing filter consists on a filter able to remove any frequency component higher than the cut-off frequency abruptly, presenting a magnitude of 1 p.u. and 0° phase change along the bandpass. On the other hand, practical anti-aliasing filters can only approximate the ideal filter behavior, presenting some oscillations and phase changes along the frequency spectrum. In this paper, a second and a third order Butterworth and a third order Chebyshev anti-aliasing filters are used. Since the sampling rates of the impedance-based and the traveling wave-based fault location techniques evaluated here are 960 Hz and 50 kHz (see Section 4), respectively, the cut-off frequencies must be at most 480 Hz and 25 kHz, respectively, for attending the sampling theorem. However, as the CCVT 1 frequency spectrum goes up to 10 kHz (see Section 3), the f_c was chosen to be 9 kHz for the traveling wave-based applications. The cut-off frequency used for the impedance-based routines was 180 Hz.

The second order Butterworth (H_{180B2}), third order Butterworth (H_{180B3}) and third order Chebyshev (H_{180C3}) transfer functions for f_c = 180 Hz are described in (1)–(3), respectively.

$$H_{180B2} = \frac{1.279 \cdot 10^6}{s^2 + 1599s + 1.279 \cdot 10^6}, \quad (1)$$

$$H_{180B3} = \frac{1.447 \cdot 10^9}{s^3 + 2262s^2 + 2.558 \cdot 10^6 s + 1.447 \cdot 10^9}, \quad (2)$$

$$H_{180C3} = \frac{3.625 \cdot 10^8}{s^3 + 675.5s^2 + 1.187 \cdot 10^6 s + 3.625 \cdot 10^8}. \quad (3)$$

For f_c = 9 kHz, the second order Butterworth (H_{9B2}), third order Butterworth (H_{9B3}) and third order Chebyshev (H_{9C3}) transfer functions are described in (4)–(6), respectively.

$$H_{9B2} = \frac{3.198 \cdot 10^9}{s^2 + 7.997 \cdot 10^4 s + 3.198 \cdot 10^9}, \quad (4)$$

$$H_{9B3} = \frac{1.808 \cdot 10^{14}}{s^3 + 1.131 \cdot 10^5 s^2 + 6.396 \cdot 10^9 s + 1.808 \cdot 10^{14}}, \quad (5)$$

$$H_{9C3} = \frac{4.531 \cdot 10^{13}}{s^3 + 3.377 \cdot 10^4 s^2 + 2.969 \cdot 10^9 s + 4.531 \cdot 10^{13}}. \quad (6)$$

The ideal and anti-aliasing filters frequency responses for f_c = 180 Hz and f_c = 9 kHz are shown in Fig. 2.

As illustrated in Fig. 2, there are some oscillations presented at the bandpass of the filters' magnitude and phase frequency responses, irrespective to the analyzed filter. However, the oscillations at the Chebyshev filter bandpass are more evident. These filters dynamic behavior may insert some deviations at the filters output.

3. Instrument transformers

Electromagnetic IT are essential equipment as part of protection systems, which are designed to provide accurate voltage and current replicas of the power grid signals. However, due to the IT design and topology, deviations at the secondary side may take place under faults in transmission lines, exhibiting unfaithful reproduction of the primary signals and undesired transient dynamic behavior, which may affect the fault locators and protective relays performances [1,3,5,6].

Basically, the voltage and current waveforms are delivered as input signals to a fault locator following the functional structure shown in Fig. 3, where the electric power system primary voltages (V_{pri}) and currents (I_{pri}) are scaled-down by the IT to the secondary side (V_s and I_s). The anti-aliasing filters remove frequencies higher than f_c in V_s and I_s and the filtered secondary voltages and currents (V_{sf} and I_{sf},