Electrical Power and Energy Systems 101 (2018) 243–254

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Development and modelling of a new type of sensor for detecting current transients for power system protection

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ARTICLE INFO

Keywords:
Transient based protection
Transient polarity identification
Ferrite core modelling

ABSTRACT

A new type of sensor is proposed to detect high frequency transients in currents and their initial polarities. The proposed sensing system replaces both high frequency signal sampling and processing by a simple detection coil wound on a ferrite core and an analogue electronic circuit. It is verified through laboratory experiments that transient occurrence, occurrence time, and initial transient polarity can be determined accurately. A detailed model of the sensor, including the dynamic hysteresis characteristics of the ferrite core, is developed and implemented on an electromagnetic transient simulation software, and verified through experimental measurements. Application of the developed model to simulate a transient current polarity comparison based protection scheme is demonstrated. The versatility of the proposed sensor compared to common digital signal processing based approaches, namely discrete wavelet transform and mathematical morphology, is highlighted using experimental waveforms.

1. Introduction

Conventional power system protection algorithms that operate on the phasor values of the power frequency currents and voltages have served well over many decades, but with the increasing penetration of inverter interfaced renewable energy sources [1], they are facing many challenges, mainly arising from lack of fault current contributions from inverter-interfaced sources during network faults. These problems are well documented for distribution networks with Distributed Energy Resources (DERs) [2–5], but similar problems are appearing in transmission networks as well with the interconnection of large wind and solar farms [3,4]. Thus there is renewed interest in transient based and time domain protection methods [6–9] as these techniques are less dependent on the sustained fault currents. Some commercial protection relays based on time domain principles are emerging [10]. Protection using transient signals has other advantages such as fast operation and immunity to current transformer (CT) saturation [11,12]. There are several different approaches for transient based protection: travelling wave based protection [9,13], transient directional comparison [14,15], and differential schemes based on derived quantities such as transient energy [8]. Travelling wave technique requires precise detection of travelling wave arrival times at the measurement location [16], while transient directional comparison techniques need determination of the polarity of the initial transient [14]. Differential techniques such as the method presented in [15] usually require comparison of signal components in a specific (high) frequency band. The method proposed in [6] does not require any signal comparisons but relies on polarity of the transient signals.

The general approach used in the transient based methods is to sample the input voltage or current signals at a frequency much higher than the sampling rates used in phasor based relays. Then various signal processing techniques, for example wavelet transform [14], S-transform [8], and mathematical morphology [9,17,18] are used extract the required signals. This approach generally requires high frequency, high precision sampling, and thus expensive analogue to digital (A/D) converters [9,14]. Furthermore, signal noise affects the sensitivity and performance. In some cases, the limited bandwidth of conventional CTs and voltage transformers (VTs) can become critical. Information on the practical implementation issues and limitations related to signal acquisition and conditioning are rare in the published literature [12].

Conventional current transformers (CTs) used for current measurements in power networks may not adequate for measuring high frequency transients due to limited bandwidth, magnetic saturation under fault current conditions and dispersion of transient signal due to secondary leakage inductance (typically several hundreds of μH), depending on the interested range of frequency [11,19]. Rogowski coils have been utilized for power frequency and transient current measurements due to their high bandwidth, linearity, and ability to measure large currents [20]. However, if it is required to obtain a measurement directly proportional to the primary current, Rogowski coil

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https://doi.org/10.1016/j.ijepes.2018.03.027
Received 8 November 2017; Received in revised form 21 February 2018; Accepted 19 March 2018
0142-0615/

requires an integrator since the output from a Rogowski coil is proportional to the rate of change of current going through it. Apart from that, since there are no magnetic materials in the flux path, output voltages are quite low relative to the conventional CTs. Few authors have proposed the use of open circuited coils similar to Rogowski coils but wound on ferrite cores [21–23] for transient detection. These publications however, provide only limited insight into theoretical aspects and mathematical modelling.

Some transient based protection methods [6,13,14] and fault location applications [24] only considers the initial transient polarity or the time of arrival of the transmitted/reflected travelling waves. For this kind of applications, accurate measurement of the current waveform is not necessary, but accurate detection of high frequency transients with minimal rise time is essential. In this paper, a novel sensor and signal processing circuity suitable for the above type of applications is proposed. The proposed sensing system replaces both high frequency signal sampling and processing, and relies on a simple detection coil wound on a ferrite core as proposed in [21]. Application of the proposed sensor for transient directional comparison type protection is focused in the paper, but it can be easily modified for using in travelling wave based and differential schemes. A main contribution of the paper is the development of a model for the sensor so that it can be represented in electromagnetic transient (EMT) simulations, which are widely used for investigating power system protection applications. The developed model is extensively verified using laboratory measurements. Finally, the advantages of the proposed sensor over the digital signal processing approaches is illustrated.

2. Arrangement and operation of the new current transient detector

Arrangement of the proposed new sensor for detecting current transients and their polarities is illustrated in Fig. 1. The primary element in the sensor is a coil wound on a ferrite core. A clip-on type core is preferred, because then the sensing coil can be easily clipped-on to the conductor that carries the input current. The coil, which consists of only few turns, is kept open circuited. The induced voltage on the coil is fed to the second stage of the sensor, which is a protection circuit containing a fuse and a surge suppressor. This protection circuit prevents damage to the low voltage electronics circuits of the relay due to high voltages that can be induced on the essentially open circuit coil. The third stage of the sensor is a passive high pass filter to remove the power frequency current and lower order harmonics. If desired, an optional low pass filter can be included after the high pass filter to remove unwanted noise.

The design of the ferrite core is such that a slight saturation is tolerated under power frequency currents. Thus the induced voltages can have a distorted waveform, resulting in significant amount of lower order harmonics. The cut-off frequency of the high pass filter was set to 1 kHz to block the power frequency signal and these lower order harmonics. The optional low pass filter cut-off frequency was set to 200 kHz filter out any noise. If this low pass filter is not included, the upper limit of the frequency range of the sensing system is limited by the frequency response of the ferrite core coil. Since the coil is designed with only a few secondary turns, it has a very small self-inductance and capacitance, and therefore the upper limit of coil bandwidth is imposed by the frequency response of the permeability of ferrite core. This limit is in the range of several MHz for typical ferrite materials [24].

The next stage of the sensor has two fast comparators, one with a positive threshold and the other with a negative threshold. The comparator with positive threshold detects transients with positive polarity and the one with the negative threshold detects transients with negative polarity. These thresholds need to be set well above the signal noise that is present under normal conditions. In this implementation, 100% of the noise was considered as the threshold. The last stage of the sensor is a resettable bistable latch and logic to allow only the output corresponding to the initial polarity to go high. When a transient is of oscillatory nature, both positive and negative comparators will trigger one after the other, this logic blocks the second signal. The output of the sensor can be used to detect the time of transient as well as its initial polarity precisely. Once a transient is detected, the latch need to be reset to make the sensor ready for detecting the next transient.

The input current can be either a current flowing in a high voltage conductor or a current on the secondary of a conventional current transformer (CT). When using the sensor for directly measuring the primary currents in a high voltage conductor, adequate insulation must be provided between the conductor and the ferrite core coil, similar to a conventional CT. Furthermore, coil parameters like number of turns should be adjusted accordingly while rest of the circuit can be used without any adjustments except thresholds. In this implementation we included the ferrite core coil in the secondary of primary CT considering the practical considerations but it is preferred to include the coil along line current if possible. When the sensor is used on the secondary side of a CT, insulation requirements are minimal, and the whole sensor can be mounted inside a protection relay. However, in this case, the frequency range of the detectable transients will be constrained by the bandwidth of the conventional CT, which can be limited to about 20 kHz [19].

The operating principle of the ferrite core coil sensor is similar to a Rogowski, and its output voltage is proportional to the rate of change of the input current when operating in the linear region. However, to design a coil that is operating in the linear region requires a ferrite core with a large cross section, making the sensor bulky and expensive. As it will be shown later, this is not necessary, as the objective is to detect only transients: the transients can be successfully detected even when the core is in saturation. When the core is saturating, the output

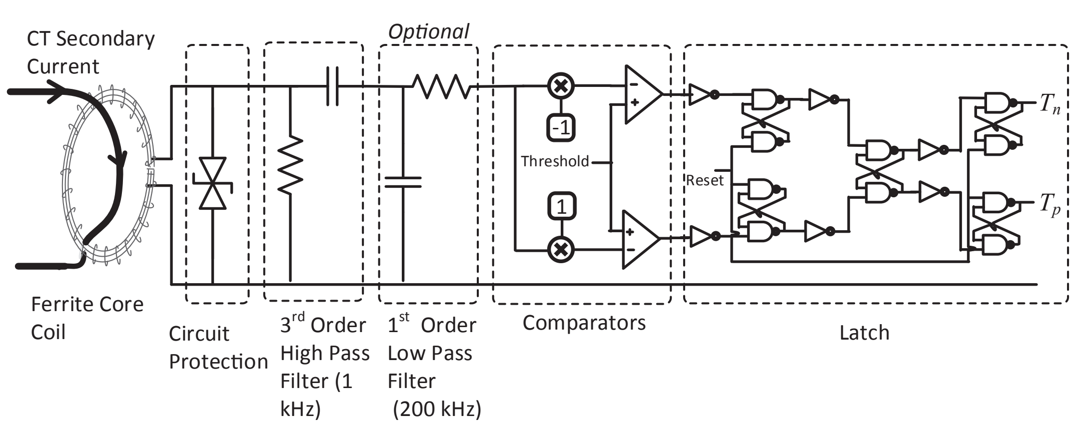

Fig. 1. Current transient detection sensor.