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Disturbance Detection in the MV and the LV Distribution Networks Using Time-Domain Method

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Abstract—With the growing need for disturbance-free power distribution, there has been significant focus under the ‘Smart Grid’ initiative on fault and disturbance analysis. Compared to the high voltage (HV) transmission systems where high-end relays can be used, medium- and low-voltage (MV, LV) distribution systems employ low-end relays for cost reason. Therefore, computationally inexpensive signal processing algorithms are needed for disturbance identification at the MV and the LV distribution systems. In this paper, a novel amplitude tracking square wave concept is presented, which can effectively represent the complex sinusoidal signals under disturbance. The amplitude tracking square wave is very sensitive to any degradation introduced in the sinusoidal signals due to disturbances. These are typically reflected in the time-domain as spikes in the square wave, without requiring any frequency analysis. This makes it particularly attractive for embedding into the MV and the LV relays with limited computational resources. Successful application of the algorithm on real disturbance records substantiate its potential.

Index Terms—Distribution automation, disturbance analysis, fault detection, fault identification, sinusoid, square wave, sinusoid to square wave conversion, signal representation, smart grid.

I. INTRODUCTION

POWER systems disturbance analysis plays an important role in secure and reliable electrical power supply. Digital recording technology has opened up a new dimension in the quantity and quality of fault and disturbance data acquisition, resulting in the availability of a huge amount of new information to the power engineers. Information from the analysis of digital records can provide much needed insight into the behavior of the power system as well as the performance of the protection equipments. However, manual analysis of these records is both time-consuming and complex. Today the challenge is to automatically convert data into knowledge, which frees the human resources to quickly implement corrective or preventive action, which is a key focus area in the ‘Smart Grid’ initiative.

With the growing need for disturbance-free power distribution for smart grid, there has been significant focus on fault and disturbance analysis [1]. With the increasing applications of advanced signal processing, machine learning, nonlinear modeling, etc., the topic of power systems disturbance analysis has truly become an interdisciplinary one [2]. Applications of phasor measurement units (PMU) [1],[3], digital fault

recorders (DFR) [4], etc. have opened up enormous possibilities.

From the signal processing side, disturbance analysis techniques often utilize the Fourier transform [5],[6], the wavelet transform [7]–[9], the Kalman filter and the system identification [10], etc. There has been also considerable focus on utilization of the machine learning techniques, e.g., artificial neural networks [2],[11],[12], support vector machine [2],[13], fuzzy logic [2], etc. Nevertheless, the need for enhanced and easily implementable algorithms remains critical.

This is particularly important for the disturbance detection in the medium voltage (MV, typically < 35 kV) and low voltage (LV, typically < 1 kV) distribution systems. This is because in the high voltage (HV, typically > 35 kV) transmission side, relatively high-end relays, DFRs are employed. Compared to that, in the MV and the LV distribution systems, low-end intelligent electronic devices (IEDs) with very limited computational resources are applied, due to cost reasons [14].

Power systems disturbance signals involve sinusoids, exponentials, noise signals. Therefore, although it is of high interest to embed some disturbance analysis algorithms directly into the IEDs, the task is very challenging considering the computational and resource (advanced digital signal processor, microcontrollers) requirements. Hence, some simplified algorithm which can effectively get rid of the power systems disturbance signals’ complexity, at the same time, could be easily embedded into device electronics, are of particular interest. In this paper, a novel amplitude tracking square wave concept is discussed, which can effectively represent the complex sinusoids under disturbance. The algorithm is simple enough to be implemented in the MV, LV level IEDs. Successful application of the algorithm on real disturbance records from power systems substantiate its potential.

The remainder of the paper is organized as follows. In section II, the concept of the amplitude tracking square wave is explained. Application of the amplitude tracking square wave on different real disturbance recordings are described in section III. Discussions on the results are mentioned in section IV, followed by conclusions in section V.

II. AMPLITUDE TRACKING SQUARE WAVE

The concept of amplitude tracking square wave is described below. We consider a sinusoidal signal $s(t)$ of frequency f Hz, sampled at f_s Hz. Then, we generate a representative square wave $x(t)$ using the amplitude of the signal $s(t)$. We will consider that the square wave has two levels $+1$ and -1 . This could also be $+A$ and $-A$, where A indicates some gain parameter. In power systems, transformation of the sinusoidal

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signal into a square wave is typically done based on the zero crossing time (ZCT) [15]. It can be defined as simply the sign function of a sinusoid:

$$x(t) = \text{sign}(s(t)), \quad (1)$$

where,

$$s(t) = A \sin(\omega t + \phi), \quad (2)$$

A is the amplitude, $\omega = 2\pi f$ is the angular frequency, f (in Hz) is the supply frequency, and ϕ is the phase angle. From (1), $x(t)$ would be 1 when $s(t)$ is positive, and -1 when $s(t)$ is negative. To improve the accuracy of the ZCT, linear interpolation is also applied [15].

For the proposed amplitude tracking square wave, we would not use the direction of the sinusoid as done for the ZCT signals. Instead, we would compare the amplitude values of the two contiguous samples of $s(t)$. The amplitude tracking square wave $x(t)$ is defined as follows.

$$\begin{cases} x(t) = 0, & \text{at } t = 0, \\ = 1, & \text{if } t > 0 \text{ and } s(t) > s(t-1), \\ = -1, & \text{if } t > 0 \text{ and } s(t) \leq s(t-1). \end{cases} \quad (3)$$

That is, the starting sample in $x(t)$ is zero; after that $x(t)$ would be 1 when the current sample of $s(t)$ is greater than its previous sample, otherwise $x(t)$ would be -1 . So, to compute each samples of $x(t)$, we would need to compare only two contiguous samples of $s(t)$.

An example of the amplitude tracking square wave is shown in Fig. 1. In Fig. 1, plot (i) shows roughly two cycles of a sinusoidal current signal of 50 Hz supply frequency, sampled at 2.5 kHz, and plot (ii), the amplitude tracking square wave. It is readily visible from Fig. 1 that the square wave defined in (3), under normal condition would capture periodicity of the sinusoid, following the property of sinusoid. More precisely, if the pulse duration of the square wave be d samples, then under normal condition, it would capture half the period of the sinusoid. That is,

$$d = \frac{f_s}{2f}, \quad (4)$$

where, f is the supply frequency in Hz, and f_s is the sampling frequency in Hz. Equation (4) can be easily verified in Fig. 1, counting the samples in plot (ii) between sample numbers 40 and 65. We get the +1 pulse duration $d = 25$, where $f_s = 2500$ Hz and $f = 50$ Hz. Following (3), the starting sample of the square wave is 0, which marks the start of recording.

The proposed amplitude tracking square wave would be highly sensitive to any transients in the sinusoid, for example, due to the disturbance and the faults. This will be readily reflected in the square wave in the time-domain. This property is very helpful in readily recognizing the power systems disturbances. This would be described in the following section.

III. APPLICATION IN POWER SYSTEMS DISTURBANCE ANALYSIS

A. Disturbance Data

The data comprising of different types of disturbances, used in this paper, were recorded using DFRs in the power network

Fig. 1. Computation of amplitude tracking square wave from sampled sinusoidal signal.

(50 Hz supply frequency) in South Africa [4]. The data is not synthetic, rather acquired from real-life network operation. The DFRs trigger due to reasons such as power network fault conditions, protection operations, breaker operation, and the like. Each DFR recording consists of analog information in the form of voltages and currents per phase as well as the neutral current. Data were acquired at a sampling frequency of 2.5 kHz, roughly for about 3s duration [4]. Following the IEEE COMTRADE standard [16], the DFR recordings are taken as input for the analysis in this work.

B. Single Line-to-Ground Fault

We would first analyze the single line-to-ground fault. The current recording for the single line-to-ground fault is shown in Fig. 2.

The current recording in Fig. 2 is shown in segmented format, for better understanding. In Fig. 2, the segment A shows the pre-fault condition, segment B fault inception and the fault, and segment C the circuit-breaker opening. The segmentation is shown here just for demonstration purpose. However, such segmentation step is very essential for automatic fault identification, relay and circuit-breaker performance monitoring [17].

The fault section (segment B in Fig. 2) along with little bit of pre-fault section and section after the circuit-breaker opening is shown in Fig. 3, plot (i). The amplitude tracking square wave for the 400 samples for this single line-to-ground fault is shown in the plot (ii) of Fig. 3.

In Fig. 3, plot (i), the A marking points to the fault inception. Before which the pre-fault section prevails. Correspondingly, in plot (ii), we see the normal pulse widths of 25 samples

Fig. 2. Current recording in single line-to-ground fault.

$\left(= \frac{2500}{2 \times 50} \right)$ between the samples 0 to 183. The point A in plot (i), appears as a spike in the square wave at exactly the same time-position of the 184-th sample. This spike clearly marks the inception of the fault. The section B in plot (i & ii) of Fig. 3, corresponds to circuit-breaker opening. In the square wave representation in plot (ii), this is effectively represented by the series of spikes. Also, in plot (ii), just before the start of segment B, we can notice a reduced pulse width between samples 305 and 320, indicating the changes in the frequency due to transient event. Therefore, we can see that the amplitude tracking square wave can effectively represent single line-to-ground type disturbances in time-domain itself. It is worthwhile to mention that localization of the disturbance inception at A in plot (i) of Fig. 3 usually requires complex time-frequency analysis, e.g., the wavelet transform [7], etc.

C. Double Line-to-Ground Fault

The current recording for the double line-to-ground fault is shown in Fig. 4.

In Fig. 4, the segment A shows the pre-fault condition, segment B fault inception and the fault, and segment C the circuit-breaker opening. The fault section along with little bit of pre-fault section and section after circuit-breaker opening, i.e., between the samples 2000 and 3000 in Fig. 4, is shown in Fig. 5, plot (i). The post-fault section in Fig. 5, plot (i), shows a typical dc offset effect, superposition of a negative exponential function on the sinusoid [2]. The amplitude tracking square wave for the 400 samples of current recording for the double line-to-ground fault is shown in the plot (ii) of Fig. 5.

In Fig. 5, plot (i), the A marking points to the fault inception, before which the pre-fault section prevails. Correspondingly, in plot (ii), we see the normal pulse widths of 25 samples $\left(= \frac{2500}{2 \times 50} \right)$ between the samples 0 to 91. The point A in plot (i), appears as a negative spike in the square wave at the time-position of the 92-nd sample. This negative spike clearly marks

Fig. 3. Current recording and the corresponding amplitude tracking square wave for single line-to-ground fault.

the inception of the fault. The section B, which corresponds to the circuit-breaker opening, is effectively represented by the series of spikes in the plot (ii). Therefore, like the single line-to-ground fault, we can see that the amplitude tracking square wave can effectively represent the double line-to-ground type disturbances in the time-domain as well.

The voltage recording for the same double line-to-ground fault is shown in Fig. 6. For the voltage recording, the fault section along with little bit of pre-fault section and section after circuit-breaker opening, i.e., between the samples 2000 and 3000 in Fig. 6, is shown in Fig. 7, plot (i). The amplitude tracking square wave for the 400 samples of voltage recording for the double line-to-ground fault is shown in the plot (ii) of Fig. 7.

In Fig. 7, plot (i), the A marking points to the fault inception, before that we can see the pre-fault section. Correspondingly in plot (ii), the section before the point A appears as normal pulse of width 25, and the point A as a negative spike at the time-position of the 105-th sample. This negative spike clearly marks the inception of the fault. The section B which corresponds to the circuit-breaker opening, is effectively represented by the series of spikes in plot (ii).

D. Transient Overvoltage

The transient voltage recording in the power network is shown in Fig. 8. In Fig. 8, plot (i), the transient overvoltage is shown for about 4 cycles (50 Hz system), followed by normal sinusoid for about 4 cycles. From plot (ii), we could notice that the amplitude tracking square wave could track that.

Fig. 4. Current recording in double line-to-ground fault.

Fig. 6. Voltage recording in double line-to-ground fault.

Fig. 5. Current recording and the corresponding amplitude tracking square wave for double line-to-ground fault.

Fig. 7. Voltage recording and the corresponding amplitude tracking square wave for double line-to-ground fault.

After 0.08s, when normal sinusoidal voltage signal prevails, the amplitude tracking square wave attains the normal pulse width. Before that, the square wave pulse width is faster, indicating disturbance. In this case, it is the transient overvoltage, recorded across a circuit-breaker in the power grid.

IV. DISCUSSION OF RESULT

The following comments can be cited on the results.

- 1) The amplitude tracking square wave, defined in (3), is very sensitive to any transient in the sinusoidal current and voltage signals due to the disturbances. These are typically reflected in the time-domain as spikes in the

square wave. This would make it possible to readily identify the onset of a disturbance. The normal pulse duration of the square wave can be calculated using (4). Deviation from the normal pulse width of the square wave would be indicative of disturbances.

- 2) Computation of the amplitude tracking square wave is simple, requiring storage of two samples of the sinusoid at any instant, and a simple comparator. This could be easily implemented into analog or digital electronics, and embedded into the MV and the LV level IEDs. A possible way could be to use a Schmitt-trigger [18] type circuit, making the threshold dynamically equal to the previous sample value.

Fig. 8. Transient voltage recording and the amplitude tracking square wave.

- 3) The amplitude tracking square wave would not require any interpolation method to improve the resolution like the ZCT signal [15] computation.
- 4) As shown in Figs. 2–8, the disturbance inception time (sample) could be located in the time-domain, without needing computationally expensive time-frequency domain algorithms like the short-term Fourier transform, or the wavelet transform. These would typically require DSPs or high-end microprocessors, and extended computation time.
- 5) However, the purpose of introducing the amplitude tracking square wave is not aimed at replacing the established fault and disturbance identification systems. Instead, this computationally inexpensive algorithm-based detection possibility can be embedded into the MV and the LV level IEDs. This could be particularly useful as a low-cost solution for the MV and the LV applications (e.g., in the distribution side protection), which is a key area in the ‘Smart Grid’ initiative.
- 6) Although disturbance recordings from a 50 Hz supply frequency system is used for the applications in this paper, the concept of the amplitude tracking square wave is generic in nature. That is, it would also work for a different supply frequency, e.g., 60 Hz.
- 7) The amplitude tracking square wave-based disturbance detection is not inherently dependent on the sampling frequency. This is because, in normal condition, the pulse duration would change depending on the supply frequency (see (4)). The disturbances would be represented by the spikes or the series of spikes, with less pulse width than in the normal condition.

V. CONCLUSION

With the growing need for disturbance-free power distribution, there has been significant focus under the ‘Smart Grid’ initiative on fault and disturbance analysis. Compared to the HV transmission systems where high-end relays can be used,

the MV and the LV distribution systems employ low-end relays for cost reason. Therefore, computationally inexpensive signal processing algorithms are needed for disturbance identification at the MV and the LV distribution systems. In this paper, a novel amplitude tracking square wave concept is presented, which can effectively represent the complex sinusoidal signals under disturbance.

For the proposed amplitude tracking square wave, it is required to compare the amplitude values of two contiguous samples of the sinusoidal voltage or current signal. The amplitude tracking square wave is very sensitive to any degradation introduced in the sinusoidal signal due to disturbances. These are typically reflected in time-domain as spikes in the square wave. This would make it possible to readily identify the onset of power systems disturbance. Application of the amplitude tracking square wave on real disturbance recordings from power systems shows promising results. The amplitude tracking square wave can be easily implemented in the MV and the LV level IEDs, with limited computational resources.

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