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2015

Yew, M. Y., & Abhisek, U. (2015). Differentiation of Fault and Load Change in HVDC System using Amplitude Tracking Square Wave. 2015 IEEE Eindhoven PowerTech Conference.

https://hdl.handle.net/10356/79267

https://doi.org/10.1109/PTC.2015.7232301

Differentiation of Fault and Load Change in HVDC System using Amplitude Tracking Square Wave

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***Abstract*—For a HVDC system, a reliable power system protection should be quick and precise in identifying fault. It is also equally important to ensure some events that could be mistaken for fault to not trigger false alarm, for example load change. Wavelet transform is one of the well-known tools that is able to achieve this purpose. In this paper, the fault analysis using a novel Amplitude Tracking Square Wave (ATSW) is studied. The algorithm is very easy to be implemented, as only time-domain analysis is involved. Notwithstanding the low complexity, it can work as effective as the wavelet transform, as proven by comparing the results obtained from these two signal processing techniques.**

***Index Terms*—Amplitude tracking square wave, fault detection, HVDC transmission, load change, wavelet transform**

I. INTRODUCTION

High voltage direct current system, or commonly known as HVDC, will be taking the conventional power system in a new direction. Since it is still met with protection issue, most of the existing HVDC systems are restricted to point-to-point system. While the prospect of multi-terminal HVDC system is promising, the protection issue has to be considered before it could be implemented in large scale. The ultimate aim of a protection strategy is to maintain the continuity of power supply by rapidly and discriminatingly isolate the fault from further damaging the system. Some events, load change for example, could be mistaken for fault because it similarly results in sudden increase in the current, thus the circuit breaker (CB) requires the information that it should not interrupt the system in this case.

The lack of definitive standard describing the functional requirement of overcurrent relay in HVDC system needs to be addressed. On one hand, the overcurrent relay is required to operate when the current fed to its coil exceeds a pre-determined value, indicating the onset of fault; on the other hand, it is usually a normal practice for the relay to be conditioned such that it should not send tripping signal to the CB for non-fault scenarios such as inrush current and load change. To achieve that, the IEC60255 [1], which specifies the rules and requirements applicable to overcurrent relay in AC system, considers the use of time delay to differentiate the permissible overcurrent from the fault. As much as the HVDC protection is concerned, such standard is still unavailable. In addition, as the DC fault penetration is relatively faster than AC fault, the time delay as it is employed in the AC protection is no longer practical in the context of HVDC system. Hence, a new protection algorithm is needed to work along with the relay to speed up the protection process.

The increasingly matured signal processing has opened up an opportunity to enable the power system protection to take on non-traditional approach so that it is better suited to problem today. The applications of phasor measurement units (PMU) [2], [3] and digital fault recorder (DFR) [4] are the evidence that disturbance analysis is hardly a standalone topic anymore. The signal processing translates the signal to different domain allowing us to see the insight of power system behavior in clearer picture. Fourier transform [5], [6], wavelet transform [7], [8], [10], [11], Kalman filter and system identification [12] have been widely discussed in literatures. There has been also considerable focus on utilization of the machine learning techniques, e.g., artificial neural networks [13]–[15], support vector machine [15], [17], fuzzy logic [15]. In regards to the requirement of differentiating load change from fault, an approach based on wavelet transform [8], [16] has been proposed to achieve that. Nevertheless, the need for an easily implemented algorithm remains critical.

This paper aims to present the application of a novel Amplitude Tracking Square Wave concept, proposed by Ukil [18], in fault detection in a two-terminal HVDC system. This algorithm is very simple to be implemented. Notwithstanding the low complexity, it is able to effectively track the disturbance in a signal much like other far advanced signal processing technique. Its application will be compared with the wavelet transform to validate its potential.

This paper is organized in following structure. The concept of Amplitude Tracking Square Wave is firstly explained in Section II. The simulation result obtained from PSCAD/EMTDC is presented in Section III, AC fault (three-phase-to-ground), DC fault (pole-to-pole) and load change are covered. The simulation is further expanded in Section IV investigating the influence of DC fault conditions on the Amplitude Tracking Square Wave. Lastly, the discussion and conclusion are given in Section V and VI respectively.

The work was supported by the Start-Up Grant *(M4081235.040)*, Nanyang Technological University, Singapore

II. Amplitude Tracking Square Wave

The concept of Amplitude Tracking Square Wave (ATSW) 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 signal is typically done based on the zero crossing time (ZCT). It can be defined as simply the sign function of a sinusoid:

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

where,

$$s(t) = A\sin(\omega t + \phi), \tag{2}$$

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 [19]. For the proposed ATSW, 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 ATSW $x(t)$ is defined as follows.

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

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 ATSW is shown in Fig. 1. In Fig. 1, plot (i) shows roughly three cycles of a sinusoidal current signal of 50 Hz supply frequency, sampled at 30 kHz, and plot (ii), the ATSW. 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,

$$d = \frac{f_s}{2f}, \tag{4}$$

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 450 and 750. We get the +1 pulse duration $d = 600$, where $f_s =$ 30000 Hz and $f = 50$ Hz. Following (3), the starting sample of the square wave is 0, which marks the start of recording.

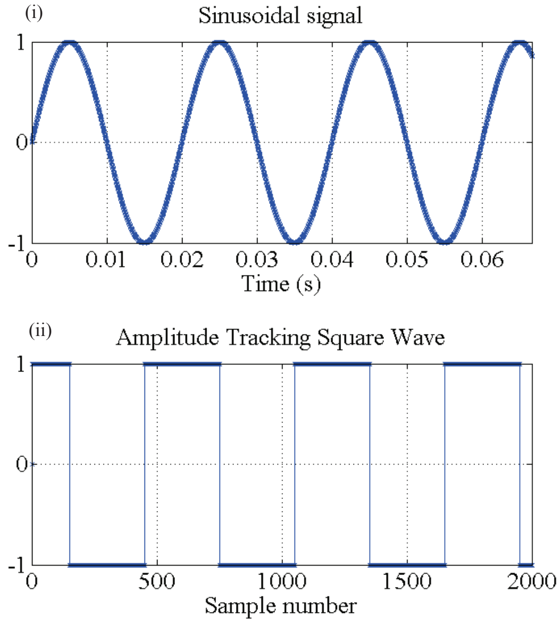

Fig. 1. Computation of Amplitude Tracking Square Wave (ATSW) from sampled sinusoidal signal.

III. Simulation Result

A two-terminal voltage source converter (VSC) HVDC system rated at 600MVA is modeled and simulated in PSCAD/EMTDC to study the fault and load change [9]. The square wave algorithm as described in (3) is slightly altered to suit the DC result, as the DC current and voltage are supposed to be constant during normal operation. Hence, the modified ATSW is defined as follows.

$$\begin{cases} x(t) = 0, & \text{if} \quad s(t) = s(t-1), \\ \quad\;\; = 1, & \text{if} \quad s(t) > s(t-1), \\ \quad\;\; = -1, & \text{if} \quad s(t) \leq s(t-1). \end{cases} \tag{5}$$

The simulated result is exported from PSCAD/EMTDC to MATLAB to perform the ATSW analysis.

A. *Three-phase-to-ground fault*

All types of AC faults share the similarity [9], therefore only three-phase-to-ground is selected as it is the worst fault in AC domain for this analysis.

To present the result with better clarity, Fig. 2 is divided into three segments. Segment a shows the pre-fault condition, segment b fault period and segment c post-fault condition. It is very clear that in segment a, because of absence of fault, the DC current remains constant, and so does the square wave. The square wave begins to appear at the same time as DC current increases during fault. The trend of DC current can be effectively captured by the square wave, as it can be seen that when DC current rises, the square wave jumps from zero to +1; an instant later, the square wave goes down to -1 signifying the drop of DC current, and the transition from one state to another state continues following the DC current oscillation.

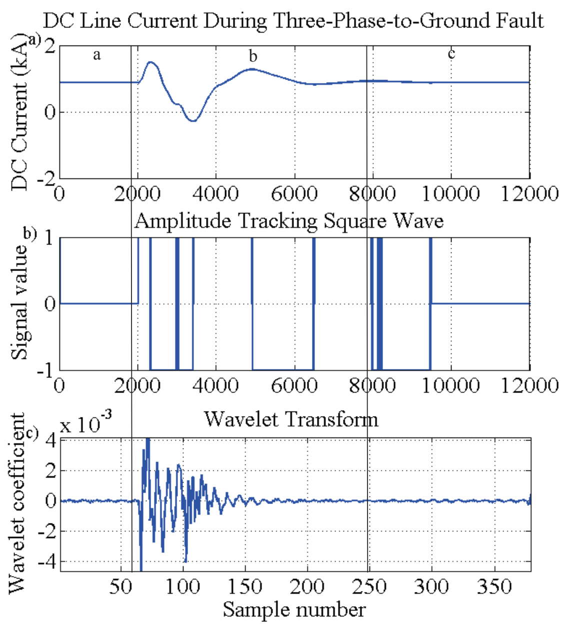

Fig. 2. The ATSW and wavelet transform for DC line current during three-phase-to-ground fault.

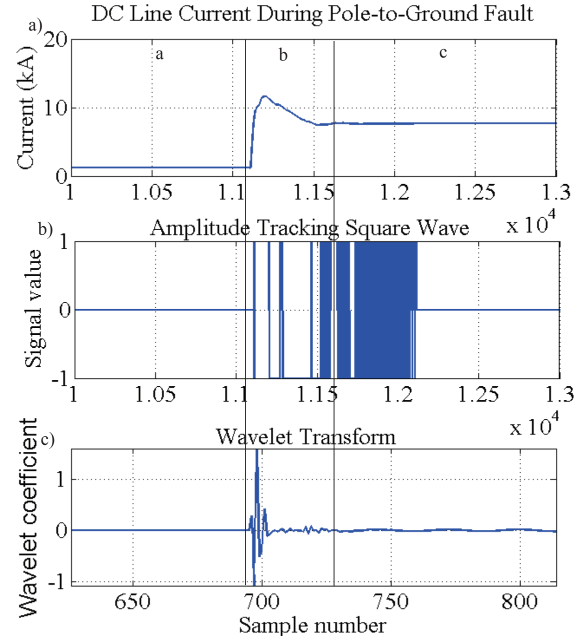

Fig. 3. The ATSW and wavelet transform for DC line current during pole-to-pole fault.

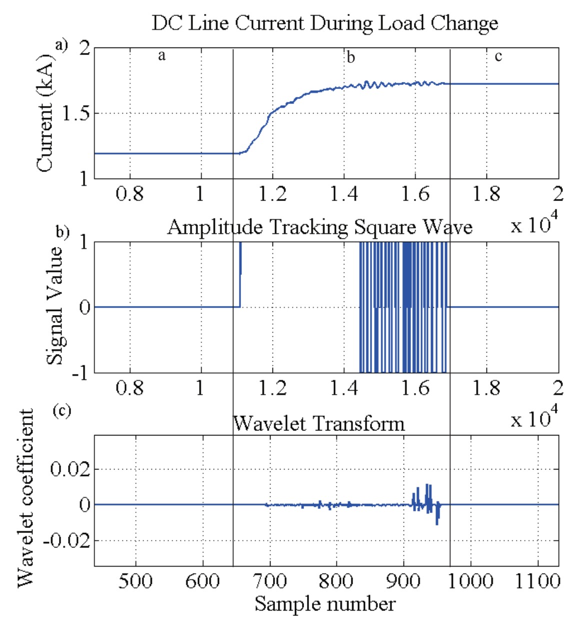

Fig. 4. The ATSW and wavelet transform for DC line current during load change.

The result obtained from the wavelet analysis [8] is cited here again to draw comparison between these two fault detection approaches. The mother wavelet employed here is Daubechies of order 3 as it is the best candidate for fault signal. The wavelet transform is capable to detect the fault with the first spike appearing in segment b, just as effective as the ATSW. The wavelet coefficient settles at zero shortly after the fault is cleared. In segment c, while the change of state still continues in square wave, the wavelet coefficient remains constant.

B. Pole-to-pole fault

The pole-to-pole fault is firstly analyzed. A fault resistance 0.01Ω is introduced at the middle of the DC overhead line between two terminals and the result is shown in Fig. 3.

Prior to the fault (segment a), the DC current is constant, so is reflected in the ATSW in Fig. 3(b) as the value is zero. As soon as the fault happens (segment b), DC current rises to the maximum. Meanwhile, in ATSW, the signal value is no longer zero and the square wave pulse begins to take shape indicating the presence of disturbance. The first pulse happens right at the time of fault inception. After the fault is cleared (segment c), the DC line current goes back to pre-fault magnitude and so does the ATSW.

On the other hand, the simulated result is post-processed using the relatively complex time-frequency analysis, or wavelet transform (see Fig. 3(c)) [8]. A similar pattern as seen in ATSW is also observed. Under normal condition the wavelet coefficient is zero. The spikes are noticeable within the segment b marking the fault occurrence in that time window.

C. Load Change

The load change is simulated by increasing the active power demand at a terminal and the result is shown in Fig. 4.

One can see that the DC line current increases to about 1.7kA in segment b. The current increases at slow rate and this observation is an important signature allowing us to differentiate load change from fault events, whereby the current typically experiences rapid increase and oscillation during fault. The signal value remains at one for rather long period in segment b, and as such, this observation confirms that the ATSW is able to capture the long rising time of current in the event of load change. Furthermore, it is worthwhile to point out that the ATSW is extremely sensitive to transience. The recurring square wave pulses can be observed after sample number 14500 signifying the corresponding oscillation in the DC current. The pulse, however, is inevitable and negligible, it does not affect our initial judgment.

Likewise, we apply the wavelet transform to the DC line current (see Fig. 4(iii)) so that we can draw a comparison between these two techniques. The low rising time is well reflected by the stable trend of wavelet coefficient in segment b. The wavelet coefficient is sufficiently low that we can say that this event is load change and the protection system should not be alarmed.

IV. Variation of DC fault condition

During the normal operation, the output of ATSW is constantly zero. Each simulated case appears to differ in term of the width of first immediate square wave as the disturbance is set to the system. That square wave width, measured in sample number, is a reflection of the time taken for DC current to reach the peak. The work in [9] has concluded that the DC fault results in the sharpest rise in the corresponding DC current, the short square width observed in our case during the DC fault also confirms that. The result is presented in Table I. The table also suggests a general idea on how to differentiate the fault from load change - DC fault having the shortest width and load change the longest. The corresponding wavelet coefficients are also shown in the table, in which the high coefficient signifies fast rising time of DC current. It becomes clear that the ATSW is in agreement with wavelet transform.

TABLE I
The first immediate square wave width for each simulated case.

Type of fault	Square wave width (sample number)	Wavelet coefficient
AC fault (three-phase-to-ground)	301	-0.00462
DC fault (pole-to-pole)	87	-1.076
Load change	3360	0.0008564

In this section, we are interested in looking into the influence of DC fault conditions on the square wave width. Keeping the system parameter constant, we will change the location of fault along the DC line and the fault resistance.

A. Influence of Fault Location

An analysis is carried out by varying the location of DC fault (pole-to-pole) along the 100km DC line. The DC current is measured at the DC side of sending-end terminal. It is known that, the nearer the fault to that terminal, the higher

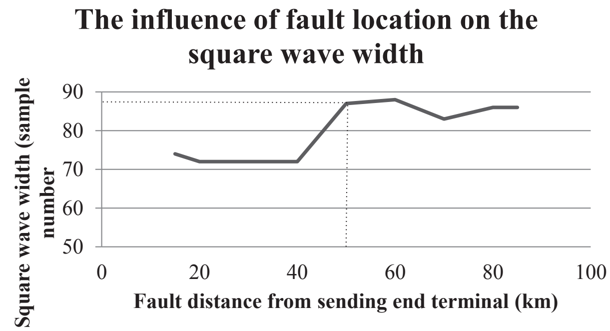

Fig. 5. The fault location is varied and the corresponding square wave width is recorded.

the peak current, and hence faster rising time. The DC current is post-processed with ATSW in order to evaluate the change of square wave width in response to fault location. The result is shown in Fig. 5.

The square wave width inevitably increases as the DC fault is moved further away from sending-end terminal, indicating the longer rising time of DC current due to fault. Using the one recorded in Table I as a reference, the fault location results in the change of width by 1%-17.2%, which is reasonable as the value is still below AC fault, as well as load change, by considerably large margin. In short, the function of ATSW is not affected by the influence of fault location.

B. Influence of Fault Resistance

The low fault resistance tends to generate large DC current due to the large DC voltage imposed across the faulted line, which has been evidently observed in Fig. 3. As it is expected that the fault resistance will change the shape of DC current, the influence of DC fault resistance, ranging from 0.01Ω-80Ω, on the square wave width is investigated. The pole-to-pole fault is set to interrupt the system at the middle of DC line. The result is shown in Fig. 6.

It is observed that increasing the DC fault resistance causes the square wave width to decrease, even shorter than the already known value in Table I. However the fault resistance is varied, the square wave width is short enough for us to interpret it as DC fault without confusing it with AC fault or load change. From this observation, the variation of fault resistance does not seem to influence the fidelity of ATSW.

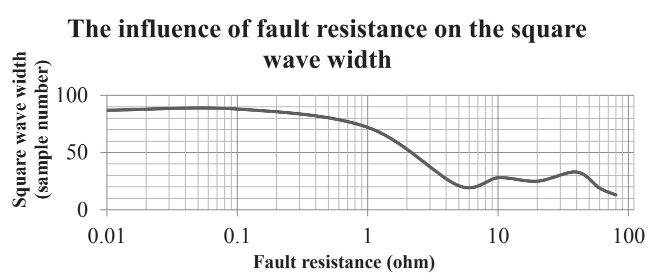

Fig. 6. The square wave width obtained for different fault resistance.

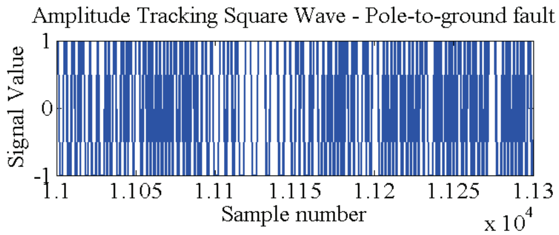

Fig. 7. Effect of using ATSW on signal corrupted with noise.

V. Discussion

The results presented here have proven that the ATSW is able to effectively represent the fault events in time-domain itself. Like wavelet transform, it can help us to differentiate the fault and load change by tracking the rising time of DC current. The first immediate square wave width is the parameter of interest that has been discussed using the example of DC fault, AC fault and load change.

There are few points to be considered:

- The ATSW is only suitable to work on clean signal as it is extremely sensitive to transience. The noise in signal will cause the waveform to be highly distorted such that series of pulses with inconsistent width (due to the harmonics, the signal behaves as if oscillation even in steady state) will overshadow the important information, as a result the fault detection might become faintly comprehensible and incorrect. For example, Fig. 7 shows the similar fault signal being processed with ATSW as in Fig. 3 containing a lot of noises. The important information is supposed to appear after sample number 11000, because of the distortion produced by the neighbor pulses, the segmentation is nearly impossible.
- The algorithm can be slightly altered to tolerate the inevitable noise in signal so that it can give a nicer looking result. This is equivalent to some filtering.
- ATSW might not be a mature solution to replace the existing fault identification system using wavelet transform. However, since it is computationally inexpensive, it can be easily implemented and used concurrently to maximize the efficiency of fault identification.
- The fault signal in this work is obtained from the 0Hz DC system, the concept of ATSW still stands regardless of different supply frequency, for example 50Hz. It is not dependent on the sampling frequency.

VI. Conclusion

In this paper, the feasibility of a novel signal processing algorithm, known as Amplitude Tracking Square Wave (ATSW), has been investigated. The implementation of ATSW is simple and computationally inexpensive. It is very sensitive to track the unhealthy symptom in a signal whereby it will result in square wave pulse with varying width. The simulation results have shown that the first immediate square wave width, which captures the rising time of fault current, is a critical parameter to determine whether the disturbance in a HVDC system is caused by fault or load change. In this regard, DC fault has the shortest width, followed by AC fault and lastly load change. With the square wave width obtained, we can differentiate the fault from load change using ATSW.

Acknowledgment

The authors would like to gratefully thank School of Electrical and Electronic Engineering, Nanyang Technological University for making this work possible. The authors also appreciate the help from Manitoba HVDC Research Centre for solving simulation issues.

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