Power Systems Frequency Estimation Using Amplitude Tracking Square Wave for Low-End Protective Relays

Article *in* Measurement · March 2019

DOI: 10.1016/j.measurement.2019.03.068

3 authors:

Abhisek Ukil
University of Auckland
229 PUBLICATIONS **2,840** CITATIONS

Yew Ming Yeap
Agency for Science, Technology and Research (A*STAR)
36 PUBLICATIONS **431** CITATIONS

Kuntal Satpathi
Nanyang Technological University
40 PUBLICATIONS **323** CITATIONS

Power Systems Frequency Estimation Using Amplitude Tracking Square Wave for Low-End Protective Relays

Abhisek Ukil*[a], Yew Ming Yeap[b], Kuntal Satpathi[c]

[a]Department of Electrical and Computer Engineering, University of Auckland, New Zealand
[b]Institute for Infocomm Research, A*STAR, Singapore
[c]School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore

Abstract

Growing emphasis on the disturbance-free electrical power distribution demands for economical and efficient smart estimation techniques in the automation architectures of the future medium voltage (MV)/ low voltage (LV) distribution networks. Unlike high-end protective relays which are typically used in the high voltage transmission systems, low-end economical protective relays are suitable for the MV/LV distribution networks. Frequency estimation is one of the prerequisites of the electrical protective relays in such systems. The low-end protective relays demand for computationally efficient signal processing algorithms for frequency estimation thus eliminating the need to integrate sophisticated hardware components and advanced software routines. In this paper, time-domain based frequency estimation is proposed, which is focused for the implementation in the low-end relays for MV/LV distribution networks. Frequency estimation is based on the novel amplitude tracking square wave (ATSW), which is fast and sensitive to disturbances in the monitored signal. Performance of the ATSW for frequency estimation is analyzed on the recorded real-world disturbance signals as well as on the various simulated case studies. Simplicity of the ATSW for low-end relays is substantiated by comparative analysis with the existing frequency

*Corresponding author
Email addresses: a.ukil@auckland.ac.nz (Abhisek Ukil*), yeap_yew_ming@i2r.a-star.edu.sg, (Yew Ming Yeap), kuntal001@e.ntu.edu.sg (Kuntal Satpathi)

estimation techniques. In addition to the frequency estimation, versatility of the ATSW is substantiated by application for transient state detection in the AC and DC power systems.

Keywords: Disturbance Detection, Frequency Estimation, Frequency- Domain Analysis, Intelligent Electronic Device, Low-End Relays, Low Voltage, Medium Voltage, Power System Protection, Protective Relays, Time-Domain Analysis.

1. Introduction

Frequency estimation plays a vital role in the operation of the power system protective relays. Fast and accurate estimation of the system frequency has major impact on the performance of the protective relay, as most of the decision output of the conventional relay is based on the phasor information. Incorrect estimation of the system frequency results in phasor oscillations [1] which may alter the behavior of the protective relay thus resulting in erroneous outputs and protection malfunctions. In order to overcome this issue, frequency estimation methods based on various frequency-domain and time-domain based algorithms have been proposed in the literature [2, 3, 4, 5, 6, 7, 8, 9]. In frequency-domain based methods, fast and accurate estimation of frequency is a challenging task, as increase in time resolution causes decrease in frequency resolution and vice versa. Many approaches based on wavelet transform are proposed, which are limited by higher computational burden thus making it unsuitable for the low-end protective relays [10]. In addition to this, improper selection of windowing functions in the frequency-domain techniques result in spectral leakages [11], which may also affect the relay behavior. Other advanced technique includes the use of phase-locked loop (PLL) [12]. Fundamentally adopted to generate a signal whose phase angle is in synchronization with that of input signal, it can be also utilized to estimate the system frequency [13]. However, due to digital filtering, implementation of PLL inevitably introduces delay that can affect the fast operation of the protective relays [14].

High voltage (HV) (typically $>$ 35 kV) transmission systems are employed to transfer bulk power over long distances. Such systems should be employed with the highly reliable protection solutions which is enabled by installing high-end protective relays with increased computational power and sophisticated protection algorithms. However, similar approaches will not be suitable for medium voltage (MV) (typically $<$ 35 kV) and low voltage (LV) (typically $<$ 1 kV) distribution systems. As compared to the HV systems, installation cost of the MV/LV systems are quite less. Thus, low-cost low-end protective relays with limited computational abilities are envisioned to be used for such applications to make the protection systems economically viable [15]. As a result, the use of sophisticated frequency estimation techniques based on the wavelet transform [16, 17], advanced digital filters [18, 19, 20, 21], iterative algorithm [22, 23], genetic algorithm [24], Bayesian learning [25], Newton-type algorithm [26], machine learning [27] are limited for the application in the HV systems as they demand for higher clock speed and large memory blocks to execute large amount of assembly level instructions. This demands for computationally efficient frequency estimation technique for implementation in the low-end relays which is the focus of this work.

With this regard, this paper proposes computationally efficient time-domain based frequency estimation technique which is based on the novel amplitude tracking square wave (ATSW) [28]. The remainder of the paper is organized as follows. Section 2 introduces the ATSW based frequency estimation technique. Section 3 presents the performance of the ATSW based frequency estimation technique on the synthetic signals and simulated test cases and then on the real world transient signals. Section 4 compares the performance of the proposed technique with the existing methods. Section 5 discusses the versatility of ATSW which apart from frequency estimation could also be used for transient state detection in AC and DC power systems. Performance of the proposed ATSW based frequency estimation is discussed in Section 6 and the paper is concluded in Section 7.

2. Proposed ATSW Based Frequency Estimation

The proposed frequency estimation technique based on ATSW is described in this section. Consider a sinusoidal signal $s(t)$ of frequency f Hz, sampled at f_s Hz. The rising and declining trend of sinusoid can be represented with a square wave, transitioning between two levels, $+1$ and -1. This could be $+A$ and $-A$, where A is the gain parameter. Traditionally, the zero crossing time (ZCT) is used to measure the continuity of sinusoidal signal. It can be simply defined by the sign function (sgn) of the input sinusoid signal under consideration. This is defined by:

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

where,

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

In (2), A is the amplitude of the sinusoid, $\omega = 2\pi f$ is the angular frequency, f (in Hz) is the operating frequency, and ϕ is the phase angle. (1) implies that $x(t)$ would be 1 when $s(t)$ is positive (> 0), and -1 when $s(t)$ is negative (< 0). To further improve the accuracy, linear interpolation has been employed to determine the ZCT [29]. On the contrary in the proposed ATSW, magnitude of sinusoid is not used as done in the ZCT signals. Instead, the amplitude values of the two successive discrete samples of the input $s[n]$ are compared. ATSW output in the discrete-domain $x[n]$, is defined as follows:

$$x[n] = \begin{cases} 0, \quad \text{at} \quad n = 0, (\text{initialisation}) \\ +1, \quad \text{if} \quad n > 0 \quad \text{and} \quad s[n] > s[n-1], \\ -1, \quad \text{if} \quad n > 0 \quad \text{and} \quad s[n] \leq s[n-1]. \end{cases} \tag{3}$$

That is, the starting sample of $x[n]$ is zero; after that $x[n]$ would be 1 when the current sample of $s[n]$ is greater than its previous sample i.e. $s[n-1]$, otherwise $x[n]$ would be -1. So, to compute each sample of $x[n]$, two successive input discrete samples, $s[n]$ and $s[n-1]$ are compared.

To illustrate the ATSW operation depicted in (3), consider a sinusoidal signal as described in (2) with $A = 1$. The first plot of Fig. 1, shows three cycles of the mentioned sinusoidal input signal of 50 Hz supply frequency, and the second plot is the ATSW output according to (3).

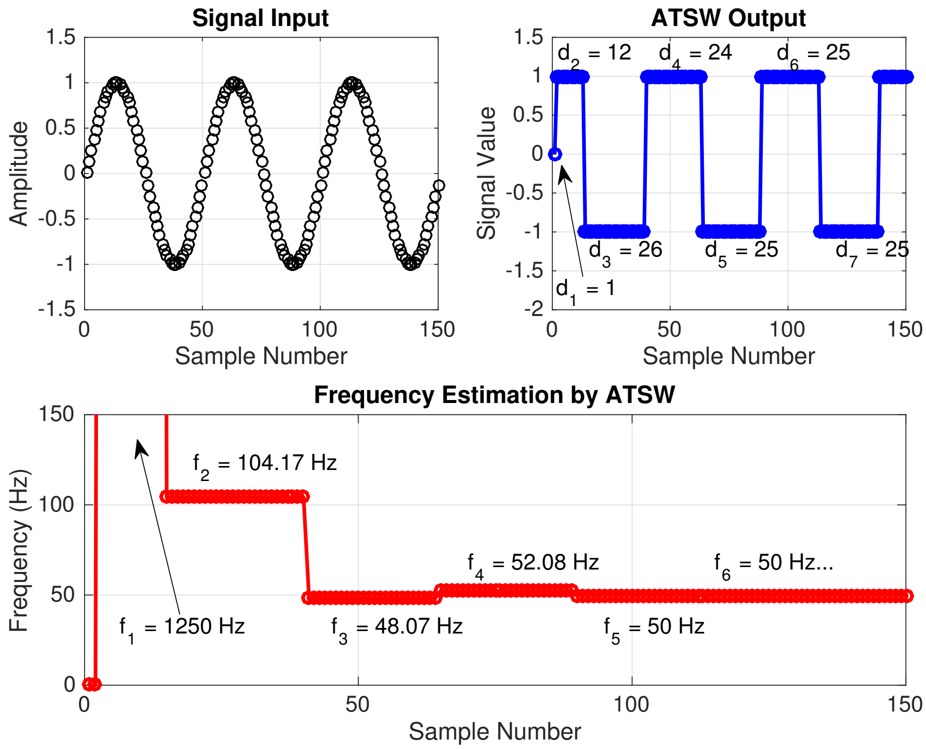

Fig. 1: Depicting the ATSW based frequency estimation for pure sinusoidal input.

Under normal condition, information regarding periodicity of the sinusoid is captured by ATSW. This information is used to estimate the frequency f of the signal, using accumulated samples d in the time-domain. d is the number of samples of ATSW output which has similar values as described in second plot of Fig. 1. As sampling frequency f_s is usually known in advance, frequency of the signal can be estimated using (4). The output of ATSW based frequency estimation for signal (2) is shown in the third plot of Fig. 1.

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

This technique has some transient response when the ATSW is initiated. As per (3), output of ATSW is 0 thus the number of accumulated sample is 1 which is shown by $d_1 = 1$ of plot 2 in Fig. 1. Accordingly, the output frequency calculated as per (4) comes out to be 1250 Hz. This is shown in the third plot of Fig. 1. The ATSW then calculates the number of accumulated samples to be 12, 26 and 24 which is illustrated by d_2, d_3 and d_4 which is marked in the second plot of Fig. 1. Consequently, the estimated frequency comes out to be 104.17 Hz, 48.07 Hz and 52.08 Hz respectively as shown in the third plot of Fig. 1. Subsequent to this initial transient events, number of accumulated samples is calculated to be 25 which is shown by $d_5, d_6, d_7, ...$ The estimated frequency then comes out to be 50 Hz (as per (4)) is shown in plot 3 of Fig. 1 which is depicted by $f_5, f_6, ...$ etc.

It is observed that the frequency estimation is done by tracking the integer values with sign change. This is expected to be very quite computationally efficient thus suitable for the low-end protective relays which is further detailed in Section 6.

3. Performance Analysis of ATSW based Frequency-Estimation

This section discusses the performance of the ATSW based frequency estimation for different test signals. Various synthetic, simulated and real-world signals are considered for this study. The fundamental frequency (f) for all test cases is 50 Hz and the sampling frequency for synthetic signals is 2500 Hz which is typically the used in some low-end protective relays [30]. In all the case studies, top plot shows the signal, middle plot shows the ATSW, and bottom plot shows the estimated frequency.

3.1. Case 1: Signal with Increase/Decrease in Signal Amplitude

The increase and decrease in signal amplitude are very common in the power system. They may signify load changes and transient condition. Under such conditions, the ATSW method should be able to correctly estimate the frequency of the input signal. The sudden increase in the amplitude of signal is shown in (5). Under such conditions, the ATSW based frequency estimation is given by Fig. 2.

$$f(t) = \begin{cases} \cos 2\pi f t & 0 \leq t \leq t_1 \\ 2\cos 2\pi f t & t > t_1. \end{cases} \tag{5}$$

The sudden decrease in the amplitude of signal is shown in (6). Under such conditions, the estimated frequency is shown as Fig. 3.

$$f(t) = \begin{cases} \cos 2\pi f t & 0 \leq t \leq t_1 \\ 0.5\cos 2\pi f t & t > t_1. \end{cases} \tag{6}$$

3.2. Case 2: Signal with Change in Phase Angle

The change in phase angle of the signal happens in the short-circuit based transient conditions [15]. The current direction is changed which depends on

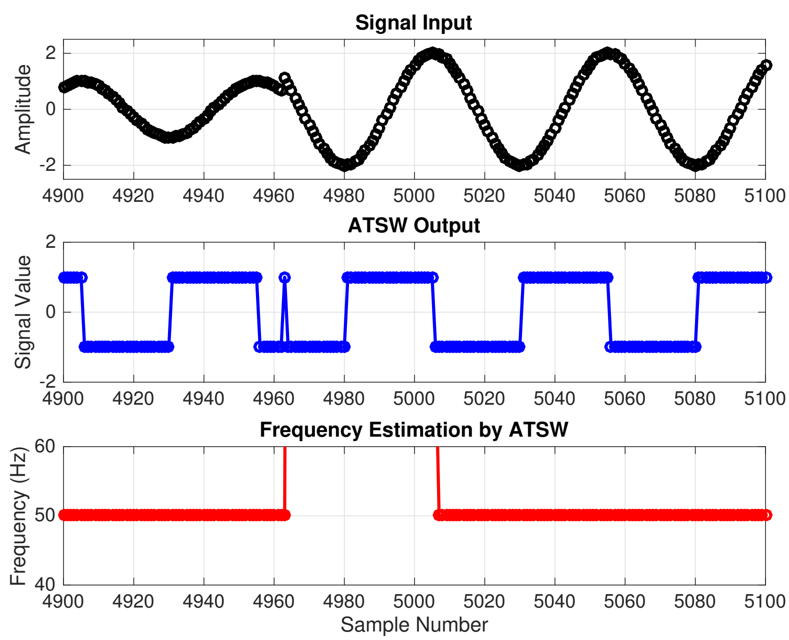

Fig. 2: ATSW based frequency estimation for step increase in the input amplitude.

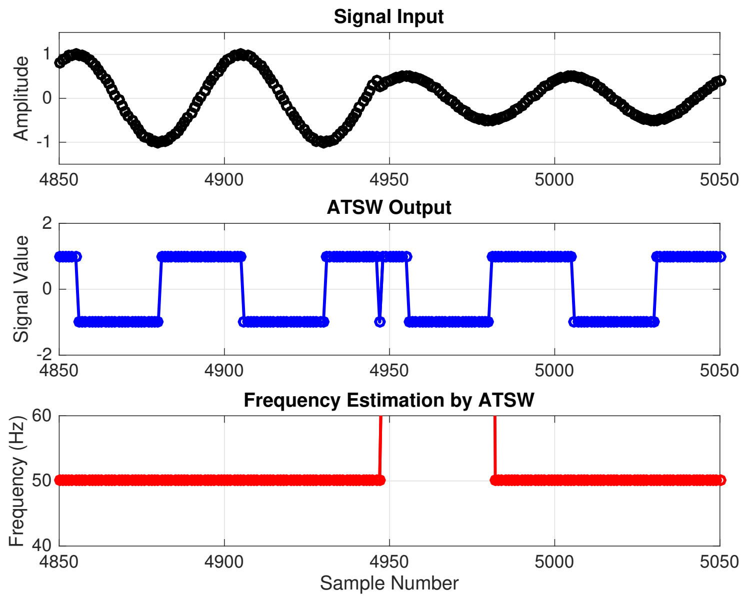

Fig. 3: ATSW based frequency estimation for step decrease in the input amplitude.

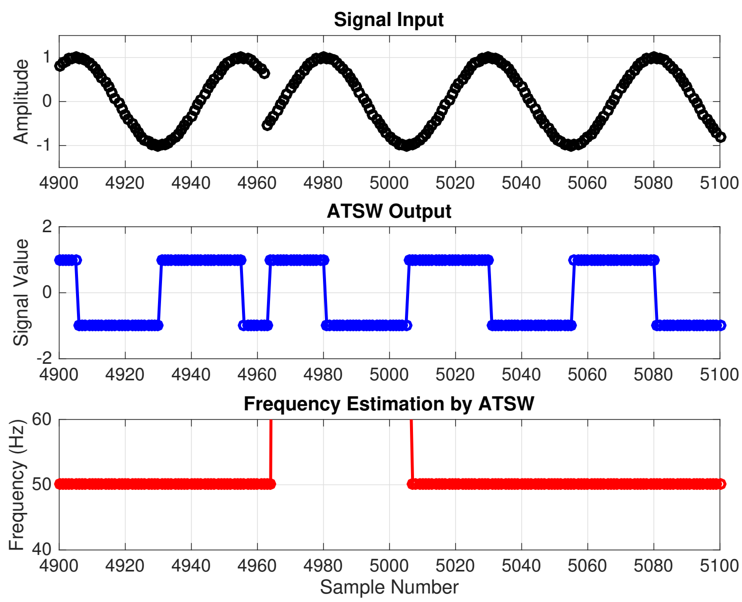

Fig. 4: ATSW based frequency estimation for change in phase angle.

the fault location and fault impedance. The signal with change in phase angle is shown in (7) and the ATSW based frequency estimation is given by Fig. 4.

$$f(t) = \begin{cases} \cos(2\pi f t) & 0 \le t \le t_1 \\ \cos(2\pi f t + \pi) & t > t_1. \end{cases} \tag{7}$$

3.3. Case 3: Signal with Increase/Decrease in Frequency

In the traditional land-based AC power systems, rapid change of the system frequency is unrealistic. However, in marine and aircraft power systems, the operating frequency of the interfaced AC generator is operated over wide range to improve the fuel efficiency [31, 32]. In such systems, the ATSW should be able to track such changes. The increase and decrease in the system frequency is shown in (8) and (9) respectively.

$$f(t) = \begin{cases} \cos(2 \cdot \pi \cdot f \cdot t) & 0 \le t \le t_1 \\ \cos(2 \cdot \pi \cdot 1.2 \cdot f \cdot t) & t > t_1. \end{cases} \tag{8}$$

$$f(t) = \begin{cases} \cos(2 \cdot \pi \cdot f \cdot t) & 0 \le t \le t_1 \\ \cos(2 \cdot \pi \cdot 0.8 \cdot f \cdot t) & t > t_1. \end{cases} \tag{9}$$

Correspondingly, the estimated frequency is shown in Fig. 5 and Fig. 6.

3.4. Case 4: Signal with Simultaneous Change of Magnitude, Phase Angle and Frequency

Simultaneous change in the magnitude, frequency and phase will result in an extreme transient event which is highly unlikely to occur. In this case, the signal is the mixture of Case-1, Case-2 and Case-3 as described in 3.1, 3.2 and 3.3 respectively. The signal is represented in (10) where the magnitude, phase and frequency is changed after t_1. The ATSW based frequency estimation for this signal is shown in Fig. 7.

$$f(t) = \begin{cases} \cos(2\pi f t) & 0 \le t \le t_1 \\ 1.5\cos(2 \cdot \pi \cdot 0.8 \cdot f \cdot t + \pi) & t > t_1. \end{cases} \tag{10}$$

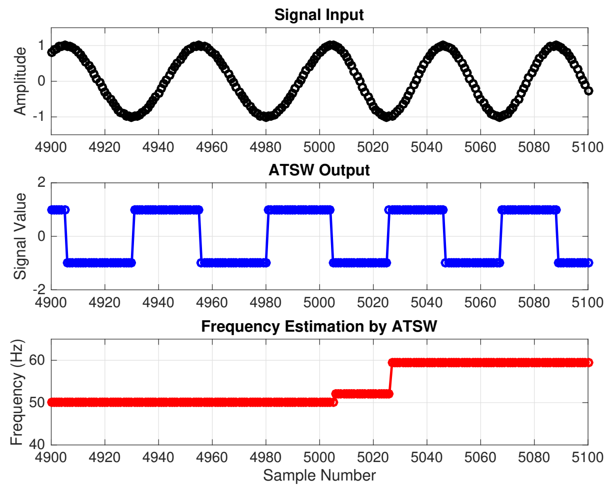

Fig. 5: Frequency estimation for step change in frequency. Frequency is changed from 50 Hz to 60 Hz.

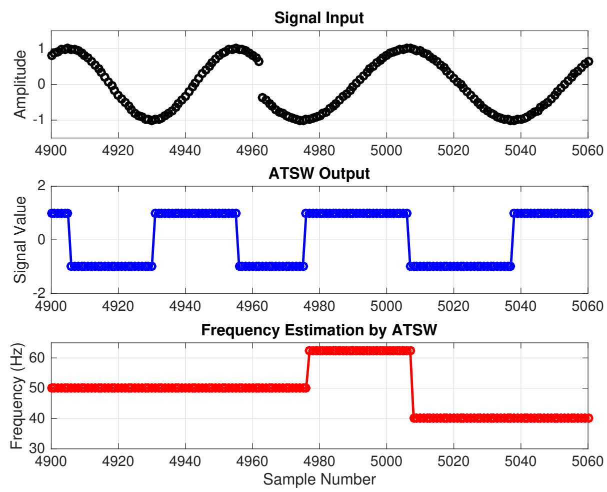

Fig. 6: Frequency estimation for step change in frequency. Frequency is changed from 50 Hz to 40 Hz.

3.5. Case 5: Signal with Harmonic Components

As the non-linear loads such as the power electronics based loads and interconnections are expected to be prevalent in the emerging power networks, system current is expected to be influenced by the harmonic currents. Odd har-

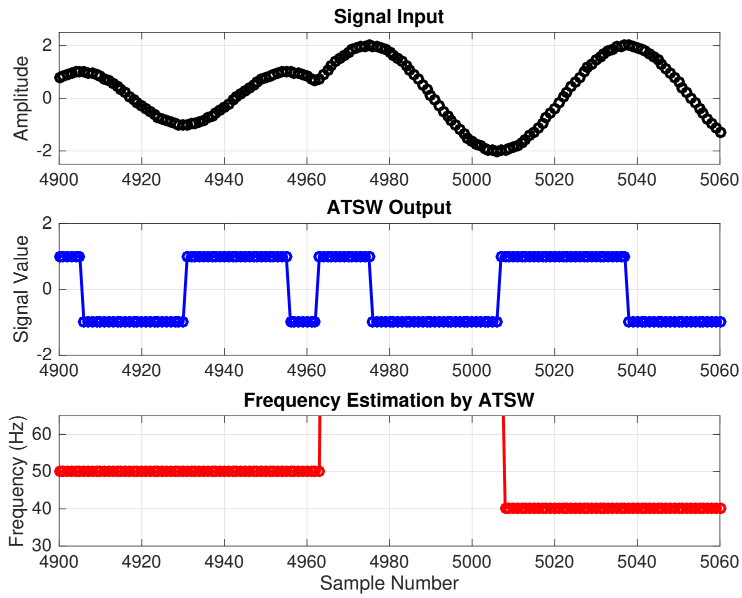

Fig. 7: Frequency estimation for change in magnitude, phase angle and frequency.

monics especially the third harmonics are expected to be dominant in such cases. ATSW should be able to measure the system frequency in such conditions. To depict such scenario, the signal ingressed with 20% third harmonic component is shown in (11) while the ATSW based frequency estimation is shown in Fig. 8.

$$f(t) = \sin 2\pi f t + 0.2 \sin 6\pi f t \tag{11}$$

3.6. Case 6: Signal with DC Offset

DC offset alters the zero-crossing time of the AC signal thus further making difficult to determine the operating frequency. However, one of the advantage of ATSW is its independence of ZCT. It is thus expected that the system frequency can be determined with ease. To illustrate this, the signal with the DC offset is shown in (12) and determining the frequency of such signal is shown in Fig. 9.

$$f(t) = \begin{cases} \cos 2\pi f t & 0 \le t \le t_1 \\ 0.5 + \cos 2\pi f t & t > t_1. \end{cases} \tag{12}$$

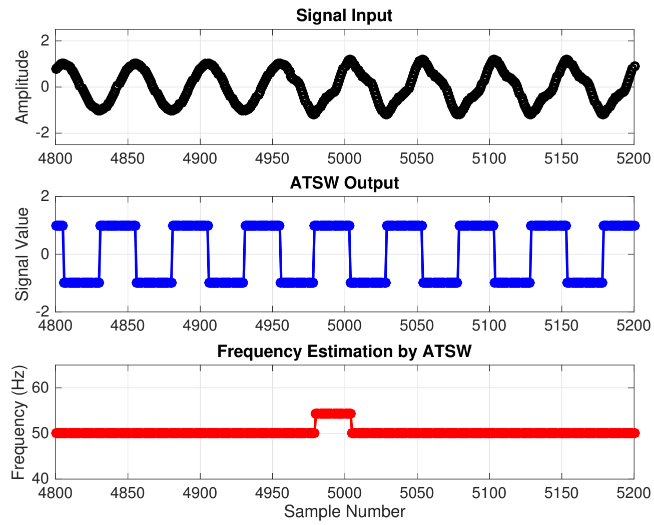

Fig. 8: Frequency estimation for signal with 20% third harmonic content.

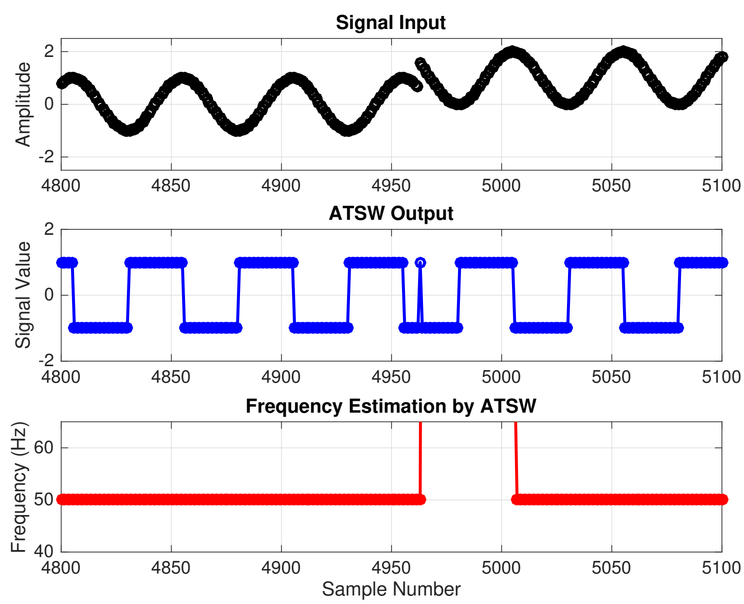

Fig. 9: Frequency estimation for signal with DC offset.

3.7. Case 7: Signal with Decaying DC Offset

AC signal superimposed with decaying exponential component is seen in the fault current in the system having higher X/R ratio. Such conditions are also

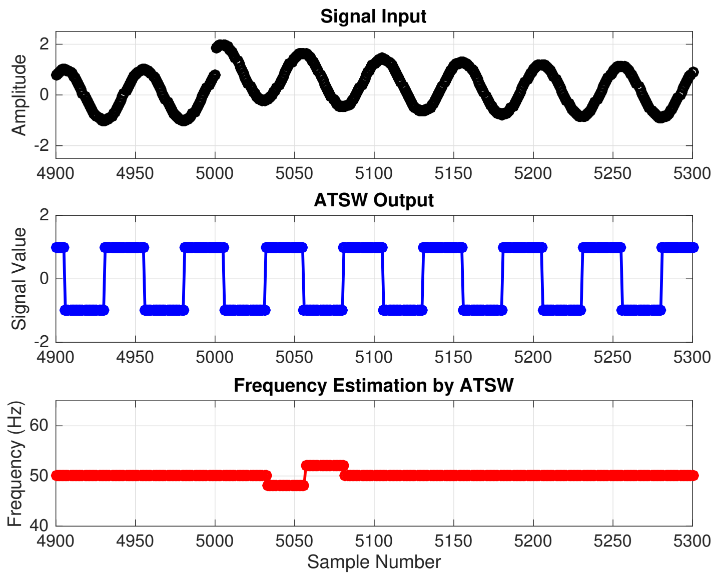

Fig. 10: Frequency estimation for signal with decaying DC offset.

observed in the voltage information delivered by capacitor voltage transformer which has a decaying DC offset information immediately after fault[33]. This condition is illustrated in (13) and the ATSW based frequency estimation is shown in Fig. 10.

$$f(t) = \begin{cases} \sin 2\pi f t & 0 \leq t \leq t_1 \\ \sin 2\pi f t + e^{-20t} & t > t_1. \end{cases} \tag{13}$$

3.8. Case 8: Operation with System Simulation

In order to analyze the performance of the proposed ATSW based frequency estimation, a test system has been considered as shown in Fig. 11. Modeling of the test system has been done in Alternative Transient Program [33]. Fig. 12 shows the extracted voltage information from the instrument transformers without filtering. As it is well known that before applying any signal processing technique the signal should be band limited to avoid aliasing. The signal information shown in Fig. 12 is passed through two stage RC low-pass filter and a sampling rate of 600 Hz is opted. Fig. 13 shows the estimated

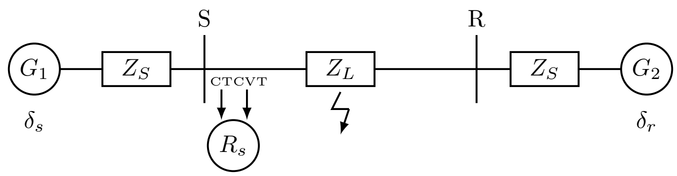

Fig. 11: Simulation based test system to depict the ATSW based frequency estimation.

frequency for each phase from voltage information. It can be observed that the proposed frequency estimation technique is able to estimate the frequency without mapping the information to frequency-domain.

3.9. Case 9: Operation on the Real World Signals

3.9.1. Transient Conditions

In order to analyze the performance of the proposed technique, real world signals are also considered in this work. The considered data is not synthetic or simulated, rather acquired from real-life network operation. These signals (50 Hz supply frequency) are obtained from power network in South Africa, using digital fault recorders (DFR) with 2.5 kHz sampling frequency for a single phase to ground transient condition at the Y-phase. The fault is removed and the voltage is restored to normal condition. The line-voltage under such event

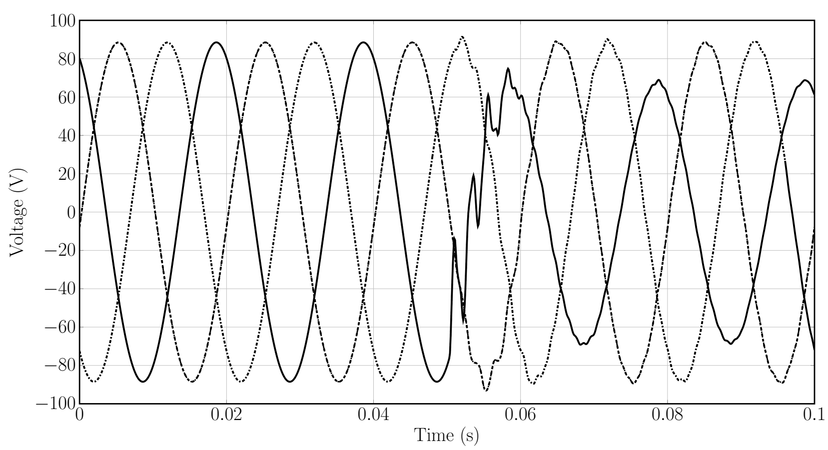

Fig. 12: Voltage information from potential transformer - without filtering.

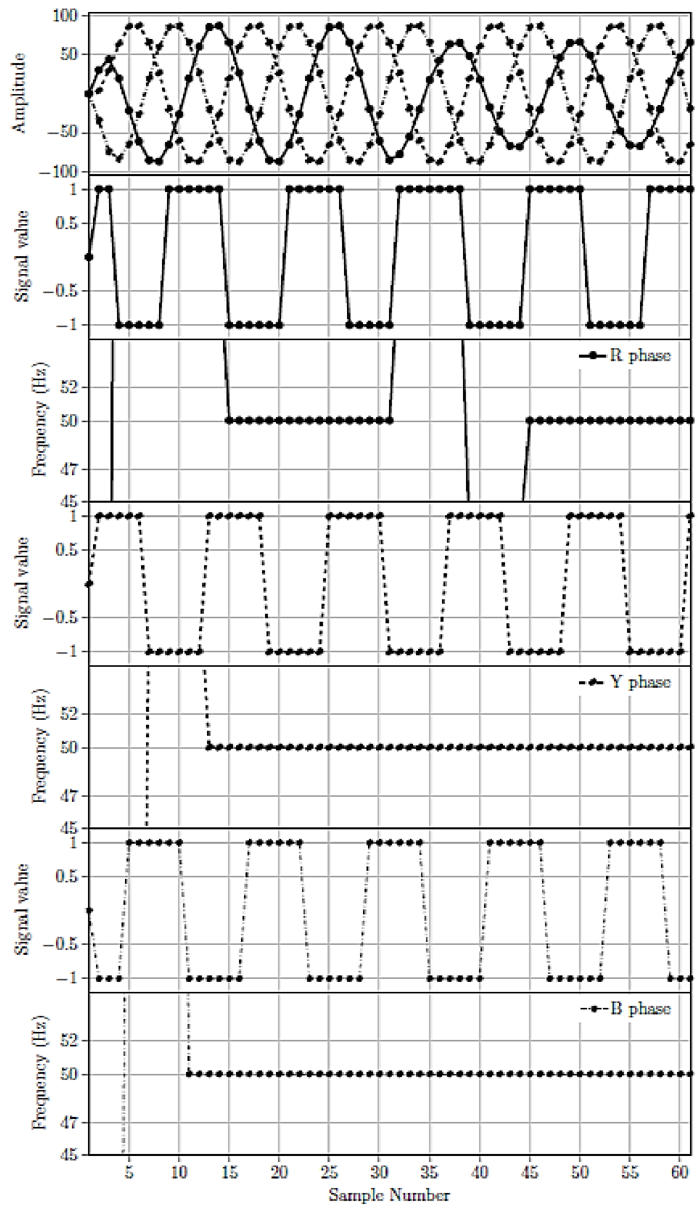

Fig. 13: Frequency estimation after low pass anti-aliasing filtering and sampling (600 Hz).

is shown in Fig. 14 which shows the intial state, transient state and final state.

Fig. 15 shows the frequency estimation by ATSW for the signal depicted

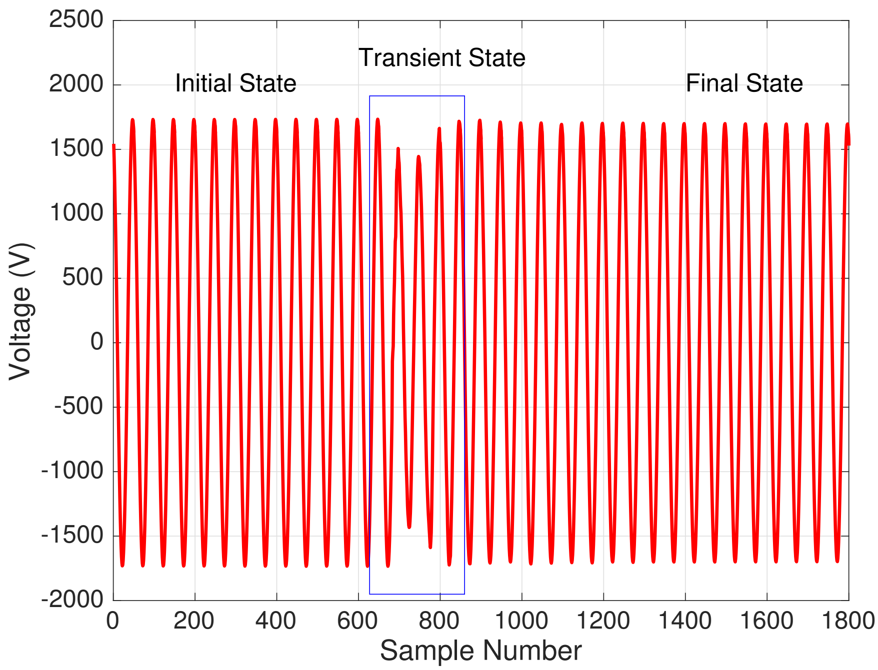

Fig. 14: Line voltage during the initial state, transient condition and the final state.

in Fig. 14. It is seen that during the transient state, the estimated frequency deviates from the nominal 50-Hz frequency. After the fault is removed the ATSW correctly estimates the 50-Hz frequency as the new sample is available.

3.9.2. Faulty Conditions

Fig. 16 shows the spectrum of the faulted phase voltages for phase Y to ground fault. During such events, the R-, Y- and B- phase voltages reduces from the nominal operating value. ATSW is applied to the Y-phase to estimate the system frequency which is shown in Fig. 17. As discussed earlier, frequency-estimation by ATSW based time-domain for the considered real-world signal is achieved by using (3). Prior to the fault (Seg. A), the estimated frequency is computed to be 50 Hz. When the fault happens (Seg. B), it is observed that the disturbance in the monitored signal is tracked immediately in time-domain using the ATSW. As the accumulated samples in square wave are used to estimate frequency, the frequency information is also reflected as soon as the fresh sample

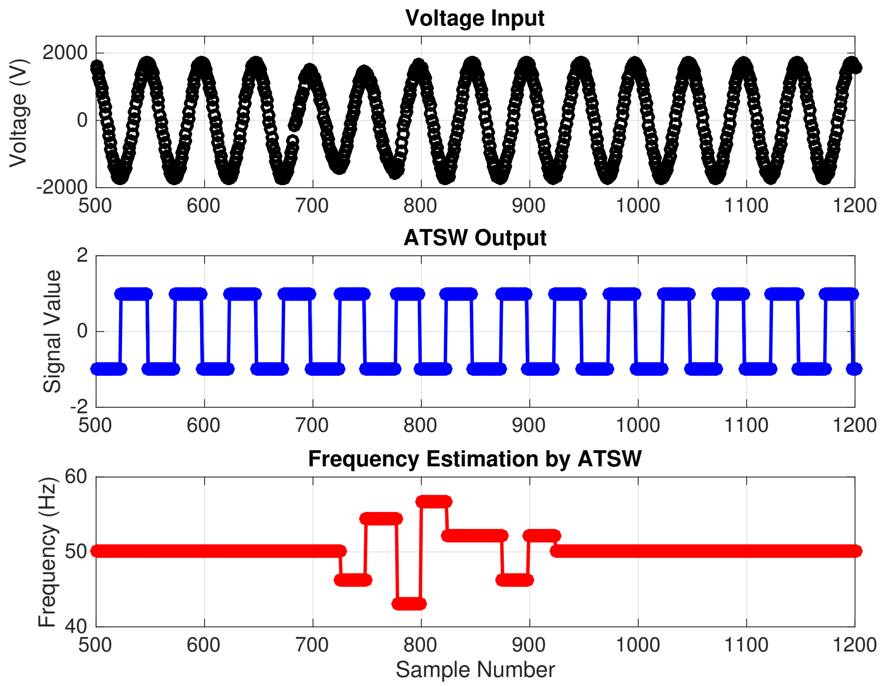

Fig. 15: ATSW based frequency estimation for line voltage with transient condition and recovery.

is available which is shown in Fig. 17. The transition from Seg. A to Seg. B is successfully captured by the ATSW. This can be an important indication of the the fault condition, thus initiating the tripping of the corresponding protective relays. Following the transient state, the variation of frequency measurement that continues in Seg. B & Seg. C is no longer of practical significance and is also shown in Fig. 17.

4. Comparison with Other Frequency Estimation Methods

In this section, proposed ATSW based frequency estimation method is compared with other available frequency estimation techniques. Comparison with one frequency-domain and one time-domain based frequency estimation methods are considered.

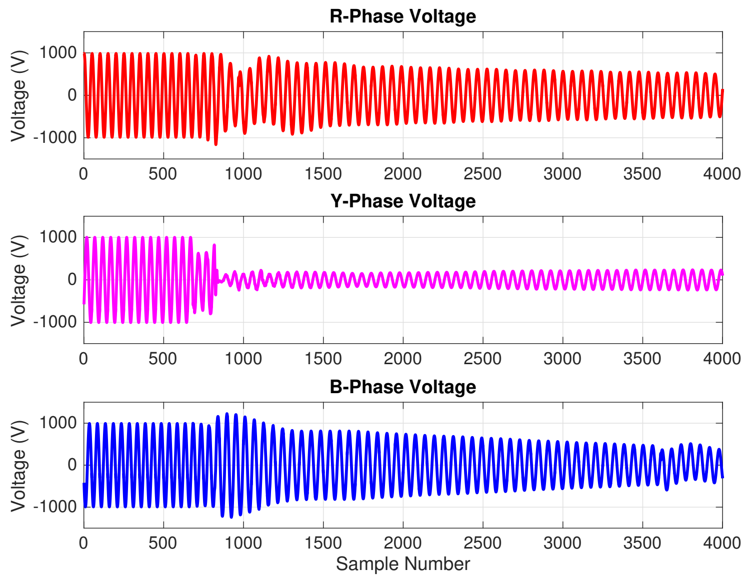

Fig. 16: Faulted phase voltage recording for single phase to ground fault at the Y-phase.

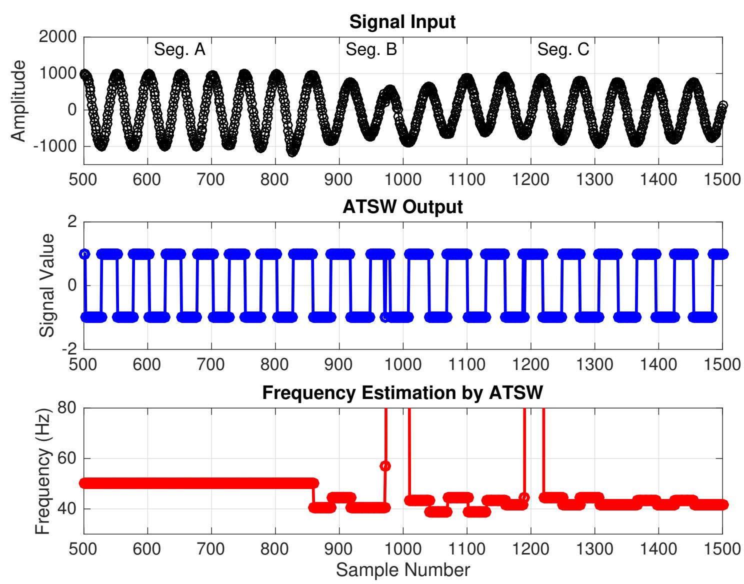

Fig. 17: ATSW based frequency estimation for line voltage with transient condition and recovery.

4.1. Time-Domain Based Frequency Estimation in High-End Relay

In this subsection, the proposed ATSW based frequency-estimation technique is compared with another time-domain approach which is used in one high-end relay [9]. The frequency is estimated using equation (14) where, f_s is the sampling frequency and N is the number of samples per period and x is estimated from samples.

$$f_{est} = \frac{f_s}{x + N}. \tag{14}$$

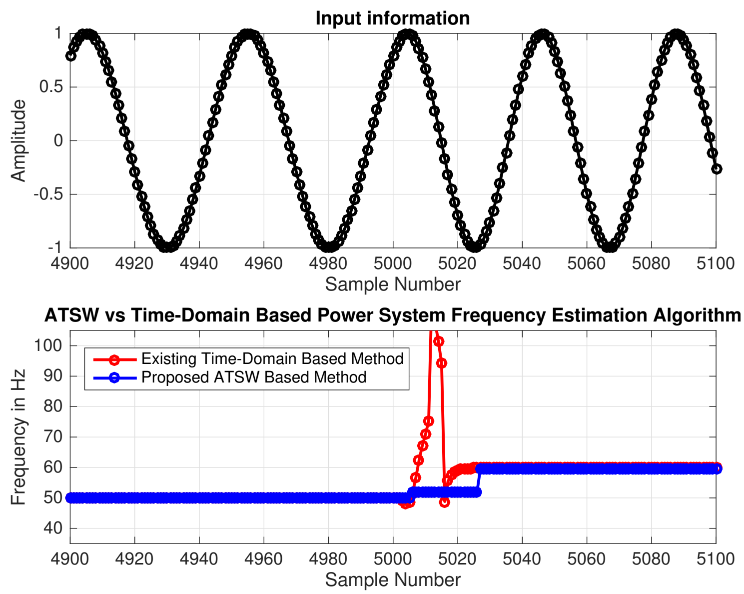

Fig. 18: Comparison of ATSW and existing time-domain based frequency estimation for simulated test system when the frequency is increased from 50 Hz to 60 Hz.

Fig. 18 and Fig. 19 show the performance of the existing time-domain based frequency estimation and the proposed ATSW based frequency estimation for simulated and real-world test cases. Simulation based test case illustrates the change in frequency from 50 Hz to 60 Hz which is similar to Case 3 described in Section 3.3. The real-world test system is illustrated by the faulted Phase-Y voltage shown in Fig. 16. During sudden change in frequency in the simulated test case, spike in frequency is observed in the existing time-domain based frequency estimation. For the transient condition in the real world signals, both

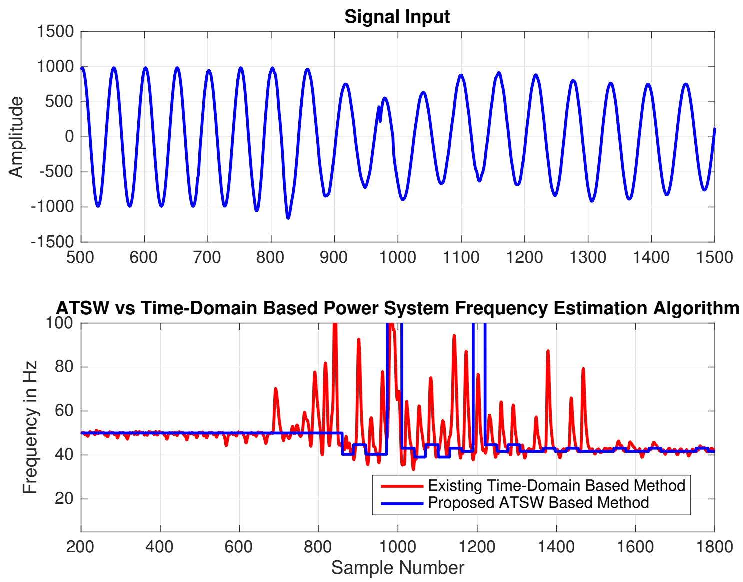

Fig. 19: Comparison of ATSW and existing time-domain based frequency estimation for real-world signals for line-ground fault at Y-phase.

the existing time-domain based method and ATSW based frequency-estimation has a number of spikes. Spikes in the ATSW based frequency-estimation is dependent on the number of samples accumulated as per (3). However, the spike in the existing time-domain based frequency estimation occurs as the input information is not fully filtered and pre-processed as estimation algorithms are typically applied after signal pre-processing.

4.2. Frequency Domain – Using Differentiation Filter

This frequency-domain method using the differentiation filter relies on the three phase information to estimate the frequency [18]. This operation is achieved by computing the instantaneous phase angle by demodulation techniques [34]. As the focus is towards low-end relay application, in this work, non-recursive differentiation filter with fixed window length has been implemented. The comparison of the existing frequency-domain based method and ATSW based frequency estimation technique for pre-fault and fault condition has been carried out for the real-world signals and is shown in Fig. 20.

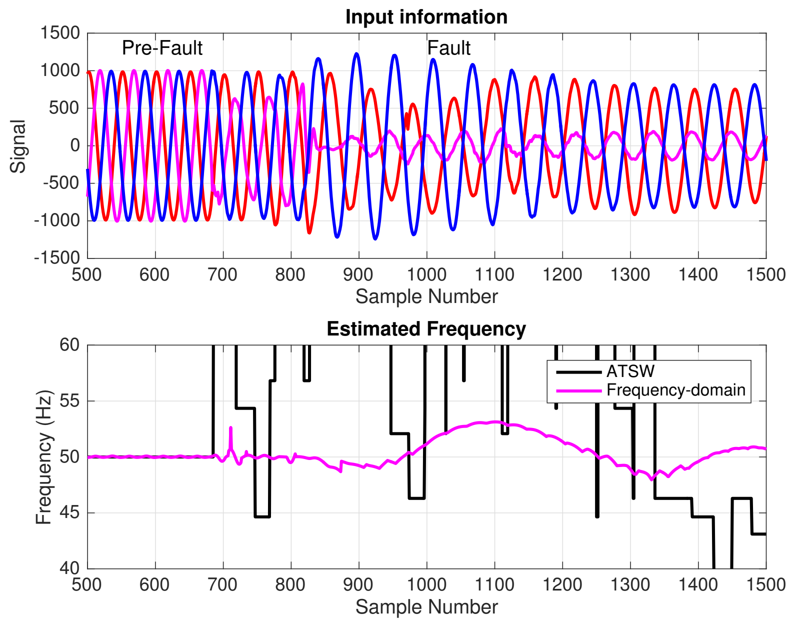

Fig. 20: Frequency estimation by ATSW and differentiation filter for pre-fault and fault condition for real-world signals.

It can be observed from Fig. 20 that the faulted phase shows large variation in estimated values when compared to the healthy phase. This is due to the fact that the proposed technique relies on single phase information, where as the considered frequency-domain approach relies on three phase information for frequency estimation. This feature, i.e. frequency estimation using single phase information is important in low-end relays. Dependence on the single phase information results in lesser computational burden which is the prime concern the low-end protective relays.

The differentiation filter based frequency-domain estimation can additionally be improved by using optimal window length. However, this involves estimation of bias and variance for each predefined dyadic window length and then finding the optimal window using intersection of confidence intervals. As it is obvious that in all relays, frequency estimation is not the only module which will be executed, but it also has many modules which have to be executed for each sample. This will increase the computation burden to low-end relays as optimal window has to be executed for each sample. In addition to this, the use of Clarke transformation for orthogonal component estimation, not only involves memory, but also involves floating point operations which is not the case in the proposed approach.

5. Implementation and Other Applications of ATSW

5.1. Implementation in Protective Relays

Evolution of the protective relays over years is shown in Fig. 21 [35, 36]. Earlier versions of the protective relays were electromechanical type which were superseded by the solid-state relays in 1980s. However, with the advent of efficient microprocessor technologies, digital relays are widely implemented in the recent years. Dedicated third generation digital protective relays to protect the distribution feeder has been developed by the manufacturers such as ABB, Siemens, Schneider Electric and GE/Alstom [38]. For instance ABB has developed a series of feeder protective relays named "Relion Series" [39]. Siemens have a range of protective relays for feeder protection which is named as "SIPROTEC Series" [40]. Schneider Electric has "MiCOM P11X/12X/13X/14X-series" (for overcurrent and earth fault protection) and "VAMP 200-Series" for protection and control of MV power systems [41]. GE/Alstom has developed their "MiCOM-Series" digital protective relays for the feeder protection [42].

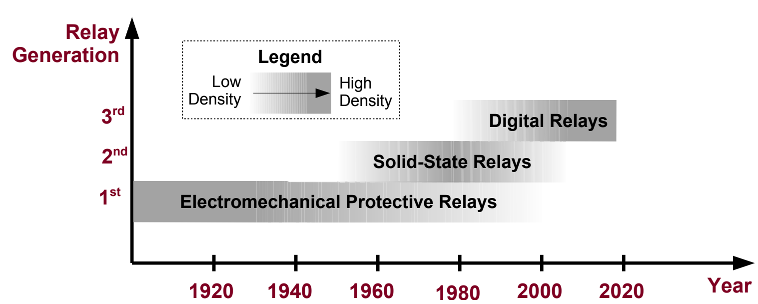

Fig. 21: Evolution of protective-relays over years [35, 36].

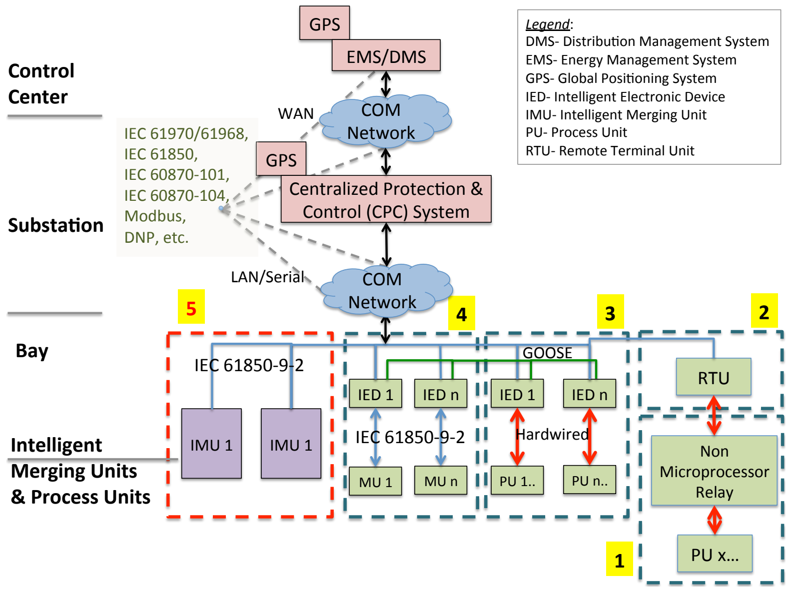

Fig. 22: Protection architecture in the AC power systems [37].

Such protective relays are also termed as the intelligent electronic devices (IEDs) and are placed in the power system network as shown in Fig. 22. Evolution of placing the IEDs with the power system network is shown in Fig. 22. As seen in Fig. 21, the first generation relies on the electromechanical systems which is also illustrated in Fig. 22. This gradually advances to the implementation of microprocessor based relays. The mentioned manufacturers have produced a wide range of protective relays which performs from the basic overcurrent protection to the advanced differential protection employing the high-fidelity communication infrastructures. These protective relays are chosen as per the target applications and also the required protection solutions. For LV/MV distribution systems low-end protective relays with limited computing ability is expected to be used. Frequency-estimation is envisaged to be an important element in such protective relays. With this regard, ATSW based frequency-estimation which is based on the integer values with sign change which can be easily implemented in such digital relays. As the proposed method does not need major computational blocks, it can be implemented in the low-end relays with limited computational

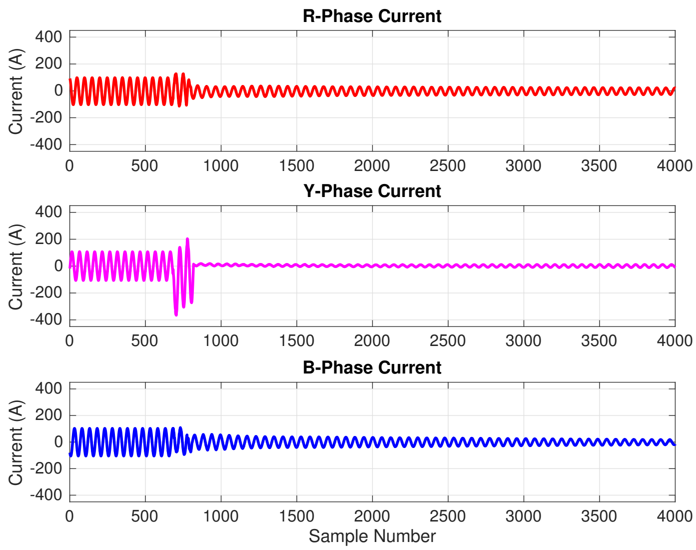

Fig. 23: Fault currents corresponding to the fault conditions depicted in Section 3.9.2.

capability.

5.2. Alternate Applications of ATSW Model

5.2.1. Transient Detection in AC System

Apart from the frequency estimation, ATSW can be instrumental for detecting the transient conditions in the AC power systems [28]. It is seen in Section 3 that the estimated frequency depends on d i.e. the accumulated samples. For sampling frequency of 2500 Hz, $d = 25$. If this d deviates from this nominal operating value, it may represent some kind of transient condition. Fig. 23 shows the fault currents corresponding to the fault conditions described in Section 3.9.2. Applying the ATSW for transient state detection is shown in Fig. 24. Line-to-ground fault F happens at 682^{nd} sample, this transient event is effectively captured by ATSW at 683^{rd} sample as the accumulated sample d_F for this event is 1.

5.2.2. Directional Element in DC System

Directional protection has emerged to be one of the useful protection strategies for the DC distribution system. It comprises of a directional element ($\mathcal{D}$)

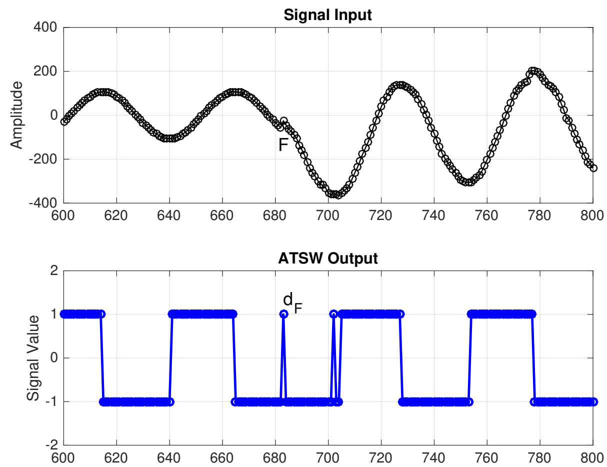

Fig. 24: Transient state detection by ATSW for Y-phase fault current as shown in Fig. 23.

working in conjunction with a fault detection algorithm. Traditionally, $\mathcal{D}$ is determined with respect to the magnitude of the DC current. This method has limitations while determining direction for the high-impedance faults [43]. Thus, $\mathcal{D}$ can be modeled as shown as:

$$\mathcal{D} = \begin{cases} 1, & \text{if} \quad i[n] - i[n-1] > +\delta \quad (\textit{Forward Direction}) \\ 0, & \text{if} \quad i[n] - i[n-1] < -\delta \quad (\textit{Reverse Direction}) \\ X, & \text{if} \quad i[n] - i[n-1] < |\delta| \quad (\textit{No Change}) \end{cases} \tag{15}$$

This modified $\mathcal{D}$ in (15) is an alternative form of (3). $\mathcal{D}$ computes the difference of the present value of the current magnitude $i[n]$ with the past value $i[n-1]$. This difference is compared against a fixed setpoint δ to determine the direction. Detailed operation of this method has been described in [43].

6. Discussion

The following comments are cited on the proposed algorithm and challenges.

1. In addition to high-end frequency estimation methods such as PLL, the proposed ATSW is a new way that can be adapted smoothly for frequency estimation. It performs relatively well. Most importantly, the algorithm is

very easy to be implemented and computationally inexpensive making it a possible candidate for low-end protective relays. There have been some literatures using PLL as a barometer of performance and comparing it with other proposed methods [44, 45], it will be of authors' future interest to do the similar work taking ATSW into comparison.

2. The CPU time (for an Intel(R) Core(TM) i5 CPU) for the proposed ATSW (Section 2), time-domain method implemented in the high-end relays (Section 4.1) and differentiation filter based frequency-domain method (Section 4.2) is shown in Table 1. It is seen that the proposed method is indeed computationally efficient. The average relative error (ARE) is calculated using (16). By ARE, fidelity of the proposed method is justifiable compared with other known methods.

$$\bar{\Delta} f = \frac{1}{N} \sum_{i=1}^{N} |f_{test} - f_{ATSW}| \tag{16a}$$

$$\text{ARE} = \frac{\bar{\Delta} f}{f_{ATSW}}, \tag{16b}$$

where $\bar{\Delta} f$=average difference between f_{test} and f_{ATSW}, N = sample number at which the fault begins to happen, f_{test} = frequency estimated by the known method, f_{ATSW} = frequency estimated by the proposed method.

3. The input requirements and major computational blocks needed to compute various frequency estimation methods are also illustrated in Table 1. The differentiation filter based method needs phase estimation blocks and thus requires Clarke transformations. It additionally needs optimum window selection for better results. On the other hand, the time-domain based high-end relays require digital filters which otherwise would result in spikes in the estimated frequency as shown in Fig. 19. The proposed ATSW and existing time-domain based method relies on single phase information while the differentiation filter requires three phase input. For the application in the low-end relays, single phase input with lower compu-

Table 1: Performance Comparison of ATSW with Existing Frequency Estimation Methods

Metric	**ATSW**	**Differentiation Filter**	**Time-Domain Based High End Relay**
Computation Time (ms)	0.0208	4.27	0.019
Average relative error [as per (16)]	–	0.16 %	6.65 %
Computation Blocks	Sign Calculation	Clarke Transformations, Phase Estimation, Optimum Window Selection	Digital Filtering Requirements
Input Requirements	Single Phase Input	Three Phase Input	Single Phase Input

tational burden are required which further justifies implementing ATSW for such cases.

4. Referring to Case 5 (Section 3.5), it is seen that the proposed method is able to tolerate minimal level of 3^{rd} harmonic. The addition of greater level of harmonic will create a dent near the phase where the wave approaches positive and negative maximum value. As a result, the downward and upward slope may confuse (3) to infer that there is a frequency change, causing the frequency measurement to be inaccurate. The influence of harmonic is outside the scope of study in this paper, since the main objective here is to analyze the transient with the lowest use of resource possible.

5. The sensitivity of the frequency measurement is largely dependent on the sampling frequency, f_s. This paper adopts sampling frequency $f_s =$ 2500 Hz which is expected to be used in the low-end protective relays. While estimating the nominal 50 Hz system, the accumulated samples are $d_{50} = 25$ Samples. Using the same f_s to test the slight changes in the line frequency differing by +/- 0.1 Hz, the following accumulated samples

would be required:

$$\begin{aligned} d_{50.1} &= \frac{2500}{2(50.1)} \\ &= 24.95 \text{ Samples.} \end{aligned} \tag{17}$$

$$\begin{aligned} d_{49.9} &= \frac{2500}{2(49.9)} \\ &= 25.05 \text{ Samples.} \end{aligned} \tag{18}$$

The accumulated samples obtained from the slight change in the line frequency is not a whole number thus posing difficulty in such scenarios. Thus, to obtain finer resolution, higher f_s would be required.

6. It is seen that the proposed method works satisfactorily for the real power system signal for pre-fault, fault and transient conditions. This is one of the biggest advantage of implementing ATSW based frequency estimation.
7. The settling time comparison of the proposed ATSW technique and the existing time-domain based frequency estimation in the high-end relays is shown in Table 2. Both are time-domain based methods and requires only single phase information. Such similarities are useful for effective comparison. In most of the scenarios, it can be inferred that the ATSW technique is faster than the existing time-domain based approach. The proposed technique works satisfactorily for the signals comprising of harmonic components (Case 5). However, the existing time-domain method would require aptly designed digital filter to suppress the spikes while estimating the frequency of the system having harmonic components. Also for the real-world transient signals (Case 9), the proposed ATSW technique is faster than the existing time-domain technique.
8. From the discussions in Section 5.2, it can be observed that ATSW is a versatile tool which can carry out multiple functions. It can measure the system frequency and can detect the transient condition in the AC power system. Also, it can be used as a directional element to devise the directional protection for the DC power systems. With such versatility

Table 2: Comparison of Settling Time of the proposed ATSW Technique and the Existing Time-Domain Methods used in High-End Relays

Scenario	**Proposed ATSW Technique**	**Existing Time-Domain Based High End Relay**
Case 1 (Amplitude Increase)	17.6 ms	18 ms
Case 1 (Amplitude Decrease)	12 ms	19.6 ms
Case 2 (Phase Angle Change)	10.4 ms	19.2 ms
Case 3 (Frequency Increase)	8.8 ms	12.4 ms
Case 3 (Frequency Decrease)	12.8 ms	14.8 ms
Case 4	15.2 ms	20 ms
Case 5	10.4 ms	Not Working
Case 6	17.6 ms	22.4 ms
Case 7	47.6 ms	423.2 ms
Case 9 (Transient Condition)*	79.6 ms	100 ms

* Settling time includes the transient condition.

and ease of application, ATSW could play a pivotal role in designing the protective relaying of hybrid AC/DC power systems.

7. Conclusion

This paper proposes ATSW based frequency estimation which is computationally efficient and operates in time-domain. Performance of the proposed ATSW based frequency estimation is validated by comparison with other time-domain and frequency-domain based frequency estimation techniques. As the proposed ATSW based frequency estimation is computed in time-domain, inherent time lag to the map information from time-domain to frequency-domain in traditional frequency-domain based approaches is not involved. This makes the proposed ATSW based frequency estimation technique fast, computationally efficient with improved reliability. Use of integer values in the proposed ATSW technique makes it computationally efficient thus suitable for application in the low-end protective relays. Computational burden can further be reduced if the frequency is estimated offline for different values of accumulated samples under different scenarios and conditions.

References

References

[1] A. G. Phadke, J. S. Thorp, Synchronized phasor measurements and their applications, Springer Science & Business Media, 2008.

[2] W. J. Premerlani, Means and method for measuring power system frequency, uS Patent 4,547,726 (Oct. 15 1985).
URL http://www.google.com/patents/US4547726

[3] P. J. Moore, R. D. Carranza, A. T. Johns, A new numeric technique for high-speed evaluation of power system frequency, IEE Proceedings - Generation, Transmission and Distribution 141 (5) (1994) 529–536. doi:10.1049/ip-gtd:19941360.

[4] D. Belega, Accuracy analysis of the normalized frequency estimation of a discrete-time sine-wave by the average-based interpolated {DFT} method, Measurement 46 (1) (2013) 593 – 602. doi:http://dx.doi.org/10.1016/j.measurement.2012.08.019.
URL http://www.sciencedirect.com/science/article/pii/S0263224112003144

[5] G. Benmouyal, System and method for exact compensation of fundamental phasors, uS Patent 6,934,654 (Aug. 23 2005).
URL http://www.google.com/patents/US6934654

[6] N. Brandt, Digital impedance relay, uS Patent 4,636,909 (Jan. 13 1987).
URL http://www.google.com/patents/US4636909

[7] D. Agre, T. Luin, Non-parametric estimation of the amplitude ratio of sinusoidal signals with common frequency, Measurement 55 (2014) 176 –

185. doi:http://dx.doi.org/10.1016/j.measurement.2014.04.039. URL http://www.sciencedirect.com/science/article/pii/S0263224114001973

[8] T. Radil, P. M. Ramos, Frequency domain parameter estimation of two common frequency single-tone signals, Measurement 43 (9) (2010) 1228 – 1239. doi:http://dx.doi.org/10.1016/j.measurement.2010.06.002. URL http://www.sciencedirect.com/science/article/pii/S0263224110001363

[9] H. Seyedi, M. Sanaye-Pasand, A new time-domain based power system frequency estimation algorithm, European Transactions on Electrical Power 22 (4) (2012) 433–448.

[10] S. M. Brahma, R. G. Kavasseri, Investigating the performance of discrete wavelet transform for phasor estimation in digital relays, in: Proc. Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE, Pittsburgh, USA, 2008. doi:10.1109/PES.2008.4596113.

[11] E. O. Brigham, The Fast Fourier Transform, Englewood Cliffs, NJ: Prentice-Hall, 1974.

[12] W. C. Lindsey, C. M. Chie, A survey of digital phase-locked loops, Proceedings of the IEEE 69 (4) (1981) 410–431. doi:10.1109/PROC.1981.11986.

[13] M. Karimi-Ghartemani, H. Karimi, M. R. Iravani, A magnitude/phase-locked loop system based on estimation of frequency and in-phase/quadrature-phase amplitudes, IEEE Transactions on Industrial Electronics 51 (2) (2004) 511–517. doi:10.1109/TIE.2004.825282.

[14] A. H. Norouzi, A. M. Sharaf, Two control schemes to enhance the dynamic performance of the STATCOM and SSSC, IEEE Transactions on Power Delivery 20 (1) (2005) 435–442. doi:10.1109/TPWRD.2004.839725.

[15] A. Ukil, B. Deck, V. H. Shah, Current-only directional overcurrent protection for distribution automation: Challenges and solutions, IEEE Transactions on Smart Grid 3 (4) (2012) 1687–1694. doi:10.1109/TSG.2012.2208127.

[16] D. Bayram, S. ŞEker, Wavelet based neuro-detector for low frequencies of vibration signals in electric motors, Applied Soft Computing 13 (5) (2013) 2683–2691.

[17] L. C. M. Andrade, M. Oleskovicz, R. A. S. Fernandes, Adaptive threshold based on wavelet transform applied to the segmentation of single and combined power quality disturbances, Applied Soft Computing 38 (2016) 967–977.

[18] R. Zivanovic, An adaptive differentiation filter for tracking instantaneous frequency in power systems, IEEE Transactions on Power Delivery 22 (2) (2007) 765–771. doi:10.1109/TPWRD.2007.893368.

[19] C. A. G. Marques, M. V. Ribeiro, C. A. Duque, P. F. Ribeiro, E. A. B. da Silva, A controlled filtering method for estimating harmonics of off-nominal frequencies, IEEE Transactions on Smart Grid 3 (1) (2012) 38–49. doi:10.1109/TSG.2011.2174259.

[20] L. Zhan, Y. Liu, J. Culliss, J. Zhao, Y. Liu, Dynamic single-phase synchronized phase and frequency estimation at the distribution level, IEEE Transactions on Smart Grid 6 (4) (2015) 2013–2022. doi:10.1109/TSG.2015.2400973.

[21] S. Nanda, P. Dash, T. Chakravorti, S. Hasan, A quadratic polynomial signal model and fuzzy adaptive filter for frequency and parameter estimation of nonstationary power signals, Measurement 87 (2016) 274 – 293. doi:http://dx.doi.org/10.1016/j.measurement.2016.03.026. URL http://www.sciencedirect.com/science/article/pii/S0263224116001901

[22] X. Pan, H. Zhao, W. Zou, Y. Zhou, J. Ma, J. Wang, F. Hu, Frequency estimation of discrete time signals based on fast iterative algorithm, Measurement 82 (2016) 461 – 465. doi:http://dx.doi.org/10.1016/j.measurement.2016.01.026.
URL http://www.sciencedirect.com/science/article/pii/S0263224116000440

[23] R. Diao, Q. Meng, Frequency estimation by iterative interpolation based on leakage compensation, Measurement 59 (2015) 44 – 50. doi:http://dx.doi.org/10.1016/j.measurement.2014.09.039.
URL http://www.sciencedirect.com/science/article/pii/S0263224114004199

[24] D. V. Coury, A. C. B. Delbem, J. R. de Carvalho, M. Oleskovicz, E. V. Simoes, D. Barbosa, T. V. da Silva, Frequency estimation using a genetic algorithm with regularization implemented in FPGAs, IEEE Transactions on Smart Grid 3 (3) (2012) 1353–1361. doi:10.1109/TSG.2012.2198675.

[25] H. Ma, H. Li, Analysis of frequency dynamics in power grid: A bayesian structure learning approach, IEEE Transactions on Smart Grid 4 (1) (2013) 457–466. doi:10.1109/TSG.2012.2226066.

[26] V. V. Terzija, Improved recursive newton-type algorithm for frequency and spectra estimation in power systems, IEEE Transactions on Instrumentation and Measurement 52 (5) (2003) 1654–1659. doi:10.1109/TIM.2003.817152.

[27] E. S. Karapidakis, Machine learning for frequency estimation of power systems, Applied Soft Computing 7 (1) (2007) 105–114.

[28] A. Ukil, Disturbance detection in the MV and the LV distribution networks using time-domain method, in: Proc. 2014 IEEE PES General Meeting, Washington, USA, 2014. doi:10.1109/PESGM.2014.6938895.

[29] A. Ukil, S. Chen, A. Andenna, Detection of stator short circuit faults in three-phase induction motors using motor current zero crossing instants, Electric Power Systems Research 81 (4) (2011) 1036–1044.

[30] C. Venkatesh, K. S. Swarup, Investigating performance of numerical distance relay with higher sampling rate, in: Proc. North American Power Symposium (NAPS), 2012, Champaign, USA, 2012. doi:10.1109/NAPS.2012.6336316.

[31] K. Satpathi, V. M. Balijepalli, A. Ukil, Modeling and real-time scheduling of DC platform supply vessel for fuel efficient operation, IEEE Transactions on Transportation Electrification 3 (3) (2017) 762–778.

[32] K. Satpathi, A. Ukil, J. Pou, Short-circuit fault management in DC electric ship propulsion system: Protection requirements, review of existing technologies and future research trends, IEEE Transactions on Transportation Electrification 4 (1) (2018) 272–291.

[33] C. Venkatesh, K. S. Swarup, Performance assessment of distance protection fed by capacitor voltage transformer with electronic ferro-resonance suppression circuit, Electric Power Systems Research 112 (2014) 12–19.

[34] M. Akke, Frequency estimation by demodulation of two complex signals, IEEE Transactions on Power Delivery 12 (1) (1997) 157–163.

[35] A. Abdelmoumene, H. Bentarzi, A review on protective relays' developments and trends, Journal of Energy in Southern Africa 25 (2) (2014) 91–95.

[36] W. A. Elmore, Protective relaying: theory and applications, Vol. 1, CRC press, 2003.

[37] S. Brahma, Advancements in centralized protection and control within a substation, IEEE Transactions on Power Delivery 31 (4) (2016) 1945–1952.

[38] A. Grid, Network protection & automation guide, Alstom Grid.

[39] ABB, Recommended offering for medium-voltage switchgears: Distribution automation, Tech. rep. (2017).

[40] SIEMENS, SIPROTEC compact 7SD80, 7SJ80, 7SJ81, 7SK80, 7SK81, 7RW80, 7SC80, Tech. rep. (2016).

[41] Protection relays by range, https://www.schneider-electric.com/en/product-category/4700-protection-relays-by-range/?filter=business-6-medium-voltage-distribution-and-grid-automation, accessed: 2018-11-1.

[42] Alstom, MiCOM Alstom P14N, P14D, P94V, Tech. rep. (2014).

[43] K. Satpathi, A. Ukil, S. S. Nag, J. Pou, M. A. Zagrodnik, DC marine power system: Transient behaviour and fault management aspects, IEEE Transactions on Industrial Informatics (2018) 1–1doi:10.1109/TII.2018.2864598.

[44] H. Karimi, M. Karimi-Ghartemani, M. R. Iravani, Estimation of frequency and its rate of change for applications in power systems, IEEE Transactions on Power Delivery 19 (2) (2004) 472–480. doi:10.1109/TPWRD.2003.822957.

[45] M. Mojiri, M. Karimi-Ghartemani, A. Bakhshai, Estimation of power system frequency using an adaptive notch filter, IEEE Transactions on Instrumentation and Measurement 56 (6) (2007) 2470–2477. doi:10.1109/TIM.2007.908631.