Vijay Gajanan Neve et al. Int. Journal of Engineering Research and Applications www.ijera.com
ISSN : 2248-9622, Vol. 5, Issue 5, (Part -3) May 2015, pp.10-23

RESEARCH ARTICLE OPEN ACCESS

A comparative study for detection and measurement of voltage disturbance in online condition

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ABSTRACT
Voltage disturbance is the most important power quality problem faced by many industrial customers. It includes voltage sag, swell, spikes and harmonics. Real time detection of these voltage disturbances posed various problems. This paper compares the various methods of detection of voltage sag and swells in real time on the basis of detection time, magnitude, effect of windowing and effect of sampling frequencies. The RMS, Peak, Fourier transform and Missing Voltage algorithm are introduced and discussed in them for real time implementation. Comparative analysis reveals that quantification of voltage sag and swell is possible using these measurements. The main focus is given on to these points and all the voltage sag and swell detection technique tested online with the help of advantech card data acquisition. The voltage sag and swell events are generated by using practical experimentation in laboratory.

***Keywords* -** Power Quality, Voltage Sag, Swell, detection, RMS, Peak, Fourier Transform, Missing Voltage.

I. INTRODUCTION

Until the 1960's the main concern of consumers of electricity was the continuity of the supply, in other words the reliability of the supply. Nowadays consumers not only require reliability, but also power quality. Over the last ten years, voltage sags have become one of the main topics concerning power quality among utilities, customers and equipment manufacturers.

With the increase used of highly sophisticated electronics, microelectronic processors in various types of equipments such as computer terminals, programmable logic controllers and diagnostic systems, the demand for clean power has been increasing in the past several years. Based on the factor that are driving for power quality events, it shows that recently most of modern load whether in industrial or commercial scales are inverter-based such as adjustable-speed drives (ASDs), air condition, voltage controlled power supplies and etc. Due to the usage of sensitive load, the efficiency, energy saving, and high controllability can increased. The increment can cause the electric power disturbances will occur. The disturbances can stimulate the sensitive equipment damage and costly to repair. The cost to repair causes severe financial losses.

The voltage sag is the most frequently occurring power quality disturbance than the voltage swell. Voltage sags account for the highest percentage of equipment interruptions, i.e., 31%. Voltage sags are also major power quality problem that contributes to nuisance tripping and malfunction of sensitive equipment in industrial processes.

The impact of voltage disturbances on sensitive equipment has called for focus on detection of them [8]. While detecting the sag and swell the important parameter is to its detection time. While in quantification of voltage sag and swell, the most important parameters are magnitude and duration.

In this paper, the main focus is on to study the following voltage sag and swell detection method-

- Root Mean Square (RMS)
- Peak Method
- Fourier Transform method
- Missing voltage method

The power quality signature, or characteristic, of the disturbance identifies the type of power quality problem. The nature of the variation in the basic components of the sine wave, i.e., voltage, current, and frequency, identifies the type of power quality problem. There are various power quality problems such as transients, harmonics, notching, flicker and voltage sag and swell. The voltage sag and swell are related to the voltage magnitude variation. These disturbances affect the sensitive electronic equipment than the conventional electrical equipment.

Literature review is useful to understand in the depth knowledge of problem formulation. The following papers were obtained from a variety of publications are as under

In paper [1], presents the five algorithms to detect the voltage sag and swell. This includes RMS (root mean square) Algorithm, Peak Value Algorithm, Fourier Transformed Based algorithm, Missing voltage Algorithm and New Algorithm based on the Non Adoptive filter. The New Algorithm is compared with the existing methods of voltage sag and swell detection. The problem with these methods is that they use a windowing technique and can therefore be too slow when applied to detect voltage sags for mitigation since they use historical data. The comparison is based on the detection time. The algorithm that can extract a single non-stationary sinusoidal signal out of a given multi component input signal. The algorithm is capable of estimating the amplitude and phase angle jump.

In paper [2], compare RMS and Missing voltage algorithm. The RMS is basically an averaging technique that relies on the periodicity and the sine-wave nature of the waveform for making comparisons. RMS loses its conventional worth if the periodicity and sine wave shape features are lost, i.e. if the waveform becomes non stationary. Because of its computational method, it is essentially insensitive to polarity changes and less sensitive to phase shifts. Computations are widely used for classifying voltage sags in terms of depth and duration. Several examples show that a great deal of information about the waveform is lost using RMS computations alone. Therefore, quantification with RMS depth and duration may not be sufficient for describing non-periodic, non-sinusoidal, and phase-shifted power transient waveforms. The missing voltage can be used to see the real time variation of the waveform from the ideal, and hence the actual severity of the sag. Furthermore, it gives a more accurate indication of the duration of the event. One especially useful application of the missing voltage technique is for sizing real-time compensation devices to correct the phase voltages for sensitive industrial loads. For devices that operate on instantaneous values, RMS computations do not indicate the true severity of voltage sag or disturbance and that a great deal of information about a disturbance waveform can be lost. The missing voltage technique, combined with the RMS information, provides a more complete picture of the disturbance, and will help better quantify and describe non periodic, non-sinusoidal, and phase-shifted waveforms. Paper [3], compare the full cycle and half cycle window algorithm. The advantages and disadvantages of each method are discussed.

Paper [4], this paper presents comparison of different voltage sag and swell detection method. There are many methods have been introduced to measure and detect voltage sags. Among these are RMS Value Evaluation, Peak Value Evaluation, Missing Voltage technique and Hysteresis Voltage Control technique. In this paper, a study is carried out to observe the different techniques of voltage sag detection. Since, precise and fast voltage detection is an essential behavior for voltage sag Compensator, therefore, observation on detection time of each detection methods will also be presented. In paper [5] presents the advantages of online detection over the offline detection.

Paper [6], presents the hardware test set-up using a DSP for generation of a trigger signal for real time detection and analysis of PQ waveforms. The modified algorithm implemented makes use of a window which spans one full cycle. The RMS value at a sample of a cycle is compared with the RMS value at the corresponding sample point of the previous cycle. The difference between the two is converted to a percentage. If this percentage change is greater than a predefined tolerance (generally 10% but can be adjusted suitably) a disturbance is detected.

Paper [7] presents the different types of sags was tested on real data captured during events such as starting of induction motor, intermittent loading of welding transformer and dynamic loading of a captive diesel generator. Paper [8] presents the new hybrid methods of detecting voltage sag and swell. With the combination digital RMS technique and the kalman filter. The online RMS value is calculated recursively in order to spend less processing time when the window length is large.

This paper is organized as follows. Section 2 outlines the Background, Section 3 describes the methodology i.e detection methods for voltage sag and swell, Section 4 outlines system under study, Section 5 shows the graphical results for various cases considered separately and Section 6 draws the conclusions.

II. BACKGROUND

In this section describes the voltage sag, swells and classification of voltage sag and swell.

2.1 Voltage Sag

Voltage sags can occur on utility systems both at distribution voltages and transmission voltages. Voltage sags that occur at higher voltages will normally spread through a utility system and will be transmitted to lower voltage systems via transformers. Voltage sags can be created within an industrial complex without any influence from the utility system.

Voltage sag as defined by IEEE Standard 1159-1995, IEEE recommended practice for monitoring electric power quality, is a decrease in root mean square (RMS) voltage at the power frequency for durations from 0.5 cycles to 1 minute [8]. Typical magnitudes are between 0.1 and 0.9 pu. Voltage sags are usually caused by: Operation of Reclosers and Circuit breakers, Inrush Currents, Fault Currents, Switching on of large loads, Switching off of capacitor bank.

An induction motor will draw six to ten times its full load current during starting. This lagging current causes a voltage drop across the impedance of the system. If the current magnitude is large relative to the system available fault current, the resulting voltage sag can be significant. The effect of voltage sag mainly affects on to sensitive electronic equipment than the conventional electrical equipment. Sensitive equipment such as computers, adjustable speed drive, microprocessor and the micro-controller etc.

The three important characteristics of voltage sags are Magnitude (depth), duration and Phase Angle Jump. The magnitude of the voltage sag can be determined in a number of ways. Most existing monitor obtains the sag magnitude from the RMS voltages. There are several ways of quantifying the voltage level. The obvious examples are the magnitude of the fundamental (power frequency) component of the voltage and the peak voltage over each cycle or half cycle. The most monitor takes the lowest value. When the sag magnitude needs to be quantified in a number, one common practice is to characterize the sag through the remaining voltage during the sag. This is then given as percentage of the nominal voltage. Thus, a 70% sag in a 230 volt system means that the voltage dropped to 161V. This method of sag characterizing the sag is recommended in number of IEEE standards (493-1998, 1159-1995, and 1346-1998).

Sag Magnitude is defined as the remaining voltage during the event. 85% sag indicates that only 15% reduction in RMS voltage from nominal voltage. Thus large magnitude sag indicates less severe is the event. The 30% sag indicates that 70% reduction in RMS voltage from nominal voltage. Thus, the small magnitude sag indicates more severe is the event. The opposite will be hold for the swell. This is the important characteristics of event for quantification of sag and swell event.

Sag Duration is defined as the number of cycle during which the RMS voltage is below a given threshold. The typical value of threshold is around 90%. The start point of voltage sag is the instant at which the voltage falls below the 90% of nominal voltage and the end point of the voltage sag is the instant at which the voltage rises above the 90% of the nominal voltage. The sag duration is the time between the start point and the end point.

A short circuit in power system not only causes a drop in voltage magnitude but also a change in phase angle of the voltage. The phase angle jump occurs due to different X/R ratio at the point of common coupling. To obtain the phase angle of measured sag, phase angle of the voltage during the sag must be compared with the phase angle of the voltage before the sag. The phase angle of the voltage can be obtained from the voltage zero crossing or for the phase of fundamental component of the voltage.

A positive phase-angle shift indicates that the phase angle of during-event voltage leads the pre-event voltage. A negative phase-angle shift indicates that the phase angle of during-event voltage lags the pre-event voltage.

2.2 Voltage swells

Voltage swells occur less frequently than voltage sags. The common causes of voltage swells are single line to ground fault, energizing of large capacitor bank, switching off a large load. Swells are characterized by their magnitude (RMS value) and duration. The severity of a voltage swell during a fault condition is a function of the fault location, system impedance, and grounding. By energizing the large capacitor bank, the large capacitive reactive power is fed to the point of common coupling. Thus the more will be the capacitive reactive power thus the voltage swell occurs on to the system. By switching off a large load, such as induction motor, heavy punching machines etc. The released of inductive reactive power thus the voltage swell occurs on to the system.

The effect of voltage swell on to equipment is that, during the voltage swell condition the voltage appears at the equipment terminal is more than the nominal voltage. Due to that the more stressed on to equipment insulation. If the insulation of the equipment is not uniform, there may be chances of insulation failure and equipment damaged.

A higher than nominal voltage over the transformer terminals will increase the magnetizing current of a transformer. As the magnetizing current is heavily distorted, an increase in voltage magnitude will increase the waveform distortion. The light output and life of such lamps are critically affected by the voltage. The expected life length of an incandescent lamps significantly reduced by only a few percent increase in the voltage magnitude. The lifetime somewhat increases for lower than nominal voltages, but this cannot compensate for the decrease in lifetime due to higher than nominal voltage. The result is that a large variation in voltage leads to a reduction in lifetime compared to a constant voltage.

Voltage swell as defined by IEEE Standard 1159-1995, IEEE Recommended Practice for Monitoring Electric Power Quality, is an increase in root mean square (RMS) voltage at the power frequency for durations from 0.5 cycles to 1 minute.[8] Typical magnitudes are between 1.1 and 1.8 pu. Swells are characterized by their magnitude (RMS value) and duration. The severity of a voltage swell during a fault condition is a function of the fault location, system impedance, and grounding.

2.3 Classification of voltage sag & swell

The voltage sag and swell are further classified into the two categories such as momentary and temporary voltage sag and swell. This classification is based on the time duration. Momentary voltage sag is defined as the decrease in RMS voltage at a power frequency for duration from 0.5 cycles to 3 seconds. The magnitude of the sag event is between the 0.1pu to 0.9pu. Temporary voltage sag is defined as the decrease in RMS voltage at a power frequency for duration from 3 seconds to 1 minute. The magnitude of the sag event is between the 0.1pu to 0.9pu.

Momentary voltage swell is defined as the increase in RMS voltage at a power frequency for duration from 0.5 cycles to 3 seconds. The magnitude of the swell event is between the 1.1pu to 1.8pu. Temporary voltage swell is defined as the increase in RMS voltage at a power frequency for duration from 3seconds to 1 minute. The magnitude of the sag event is between the 1.1pu to 1.8pu.

If the voltage sag is persist for time duration more than 1 minute then it is called as Under voltage. If the voltage swell is persist for time duration more than 1 minute then it is called as Overvoltage.

III. METHODOLOGY OR DETECTION METHODS FOR VOLATGE SAG AND SWELL

Voltage sag has been the focus of considerable research in recent years. It can cause expensive downtime. Research on voltage sag detection has also grown up and it is an essential part of the voltage sag compensator. There are many methods have been introduced to measure and detect voltage sags. Among these are RMS Method, Peak Value Method, Fourier Transform Method and Missing Voltage method. These methods are explained are as under-

3.1 RMS Method

The most common processing tool for voltage measurement in power systems is the calculation of the Root Mean Square (RMS) value. The most important standards related to the measurement of power quality disturbances are, at present, IEC Standard 61000-4-30 and IEEE Standard.1159-1995. Both propose the use of RMS value of voltage supplies for voltage sag and swell detection. Root Mean Square (RMS) value of a signal can be used effectively to detect voltage sags and swell. Voltage and current measurements are often expressed in RMS values [2]. As voltage sags are initially recorded as sampled points in time, the RMS voltage will have to be calculated from the sampled time domain voltages. This is done by following equation (1):

$$V^{RMS}(i) = \sqrt{\frac{1}{N}\sum_{j=1}^{i+N-1} V^{2}(j)} \quad (1)$$

Where,
N is Number of the samples per cycle
V (j) is jth sample of the recorded voltage waveform
$V^{RMS}(i)$ is ith sample of the calculated RMS voltage

During the occurrence of sag, the RMS value drops below the nominal value. This drop is proportional to the level of sag. Similarly, during a swell, the RMS value exceeds the nominal RMS value by an amount proportional to the level of swell.

The sag and swell are the non stationary event. Thus there is a need to reset the algorithm after the occurrence of sag or swell. This can be overcome by calculating the RMS value over a moving window encompassing a fixed number of samples. The widely-used moving-window RMS value is calculated for digitally recorded data. Each of the sampled components of one cycle of the waveform is squared individually and then summed together. Then, the square root of this sum is calculated and this single value is plotted. Since, a waveform disturbance is not stationary; the window is moved incrementally along the waveform. Here used, a continuous-time RMS waveform can be achieved by sliding the window one data point to the right and the oldest data (at the left of the window) is dropped as time progresses with each increment. In order to spend less processing time, a recursive alternative can be used. This provides a significant processing time saving when N is large.

3.2 Peak Value Method

The peak voltage as a function of time can be obtained by using the following expression (2):

$$Vpeak = \max_{0<\tau<T}(|V(t-\tau)|)\,(2)$$

Where,
V_{peak} = peak value of voltage signal.
V (t) = the sampled voltage waveform.
T= is an integer multiple of one half or Full cycle.

For each sample the maximum of the absolute value of the voltage over the preceding half cycle (or full cycle) is calculated.

3.3 Fourier Transform Method

The fundamental component of the voltage is calculated by using the discrete Fourier Transform method. The complex fundamental component is calculated by following expression (3):

$$Vfund = \frac{2}{N}\sum_{n=-\infty}^{\infty} V(n)e^{(-jw_0 n)} \quad (3)$$

Where,
$W_0 = 2\pi\ (f/Fs)$.
f=frequency of supply.
Fs=sampling frequency.
V (n) = sampled voltage waveform.
N=Number of sample in one cycle.

V_{fund}= complex fundamental component of the voltage signal;

By calculation of fundamental component of the voltage has the advantage that the phase angle jump can be determined. The magnitude of the fundamental component is obtained by taking the absolute of the Vfund. The phase angle jump is determined as, Vfund=X+ jY;
Phase angle jump= arctan(Y/X);

3.4 Missing Voltage Method

The missing voltage is defined as the difference between the desired instantaneous voltage and the actual instantaneous one [1]. The missing voltage is calculated from the following expressions:

$$Vpll(t) = A\sin(wt - \Phi a) \qquad (4)$$

$$Vsag(t) = B\sin(wt - \Phi b) \qquad (5)$$

$$R = \sqrt{A^2 + B^2 - 2AB\cos(\Phi b - \Phi a)} \qquad (6)$$

$$\tan(\Psi) = \frac{A\sin(\Phi a) - B\sin(\Phi b)}{A\cos(\Phi a) - B\cos(\Phi b)} \qquad (7)$$

$$m(t) = R\sin(wt - \Psi) \qquad (8)$$

Where,
Vpll (t) =desired voltage signal.
A= peak amplitude of the desired voltage signal.
Vsag (t) =disturbed waveform.
B=peak amplitude of the disturbed waveform.
R=amplitude of missing voltage.
m (t) = the instantaneous deviation from the known reference.

The desired signal is taken as the first cycle of the prefault voltage signal. It relies on the assumption that the system frequency is constant during the sag. The technique requires the peak method to determine the amplitude of the presag and sag voltages A and B, respectively. This method is suitable for sag analysis rather than detection. The reason for this is that the sag amplitude B is not known until after the event. It requires presage and sag voltages A and B are always in phase.

In this section describes the RMS, Peak, Fourier and Missing Voltage algorithm to detect the voltage sag and swell.

IV. SYSTEM UNDER STUDY

In this section describes experimentation setup used to study the performance of above described detection methods in offline and online condition.

To study the online performance of the detection method, voltage sag and swell conditions are generated in the laboratories through tailor made experimentation setup. Desired voltage signals are captured through data acquisition card and processed through various detection method algorithms. In this section describes the hardware used during the experimentation

Fig. 1 shows the practical experimental setup that was used to conduct the experiment in laboratory. The main components required for the setup are, single phase transformer, solid state mechanical relay, induction motor, potential transformer, gain control circuit, Advantech data acquisition card, personnel computer etc. Fig. 2 shows the block diagram of practical experimental setup.

In experimentation, single phase 2KVA, 230V/230V, isolation transformer is used. It has taps that can be set from 0V to 230V in steps of 10V. Change of taps can be viewed as voltage sag conditions for online simulation. Induction motor of 2hp is used as a load which act as source of voltage sag. A step down transformer of 230/6V is used as potential transformer to provide the signal of desired magnitude for the measurement purpose. The solid state mechanical relay is used to act as a tap changer so that the voltage sag and swell conditions can be simulated online. The relay has rating of230V/10A and the operating coil of the relay is provided with the +12V DC supply.

The gain control circuit is necessary to prevent the clamping of input voltage signal and also to provide the isolation between the computer and the supply. The gain 0.5 is achieve by choosing the values of R_F = 5KΩ and R_1 = 10KΩ. The input voltage at the op-amplifier is 6V and voltage available at the output is 3V.

In this experimentation purpose Advantech data acquisition system use, specification of this system is PCLD-8710 - 100 kS/s, 12-bit, 16-ch PCI Multifunction Card - Advantech Co., Ltd.

In this way describes the practical experimental setup developed in the laboratory to detect and measurement of voltage disturbance using RMS, Peak, Fourier and missing voltage technique in real time by using MATLAB program

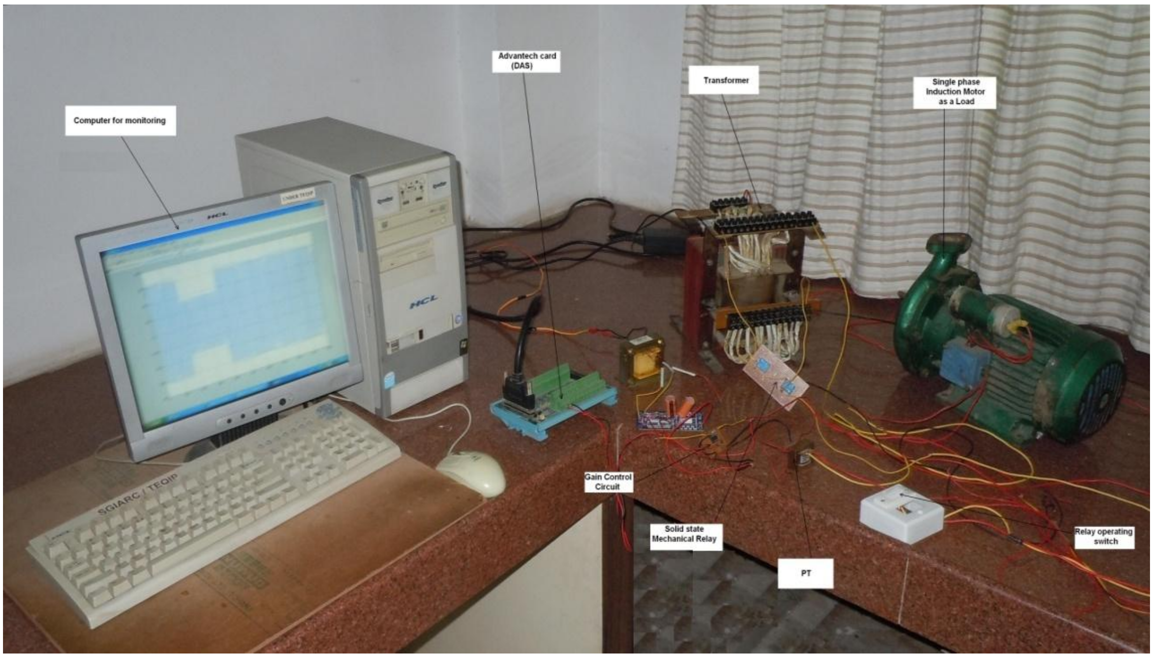

Fig. 1: Practical Experimental setup of the system

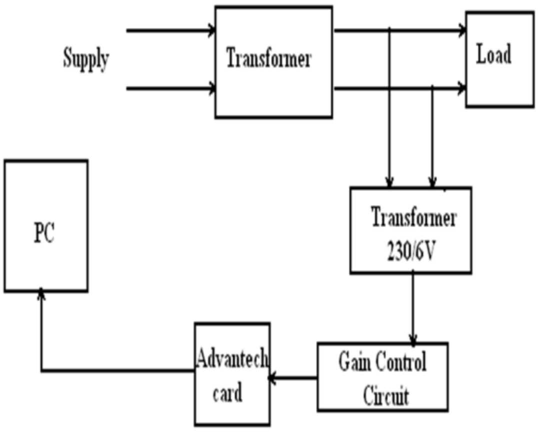

Fig. 2 Block Diagram of Practical Experimental Setup

The fig. 3 and fig. 4 shows the actual voltage sag and voltage swell signal capture in the laboratory due to induction motor tapping.

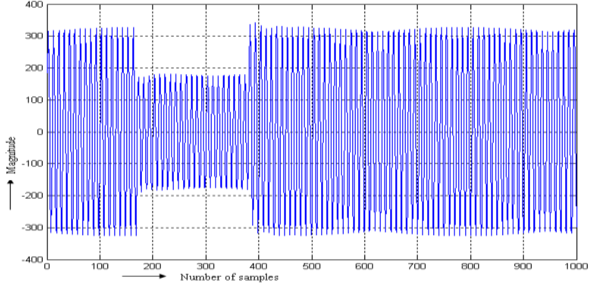

Fig. 3 Voltage Sag due to Induction Motor Tapping 110V.

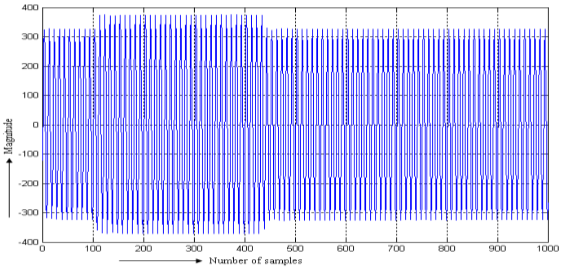

Fig. 4 Voltage Swell due to Induction Motor Tapping 40V

In this way describes the practical experimental setup developed in the laboratory to generate the voltage sag and swell of varying magnitude and duration. This experimental setup for the online and offline detection is similar only change in developed MATLAB program.

V. RESULTS AND DISCUSSIONS

In this section describes the results obtained from offline detection using all the four methods. Also the results of online detection of voltage sag and swell. The methods are compared on the basis of detection time.

The voltage sag signal was capture at sampling frequency of 500Hz, 1000Hz, 5000Hz and 10000Hz and of different depth such as 110V tapping and 80V tapping respectively. The objective is to find out minimum number of samples required i.e. window length for accurate estimation of sag and swell. Also the effect on detection time of each method as the sampling frequency increases.

The following cases were studied for analysis of Voltage Sag and Swell using RMS, Peak Value, Fourier Transform and Missing Voltage Method are as under,

- Analysis of voltage sag using full cycle and half cycle window.
- Analysis of voltage swell using full cycle and half cycle window.
- Analysis of Voltage sag using full cycle and half cycle window length at different sampling frequency.
- Analysis of Voltage swell using full cycle and half cycle window length at different sampling frequency.

Rather than we take quarter cycle windowing technique, oscillations in envelops are observed for RMS, Peak and Fourier transform methods. But in that case it is highly tedious to realize the depth, duration and detection time of voltage sag in online monitoring, so due to this neglected the analysis of voltage sag/Swell using quarter cycle window.

5.1 Discussions On Voltage Sag

The offline analysis results of all four methods for detection of voltage sag is presented below-

5.1.1 Analysis using full cycle and half cycle Window length

For analysis of voltage sag using proposed four detection methods, the sag is created by changing tap of transformer from 230V (nominal voltage) to 110 V tap in online condition. The analysis results are discussed below-

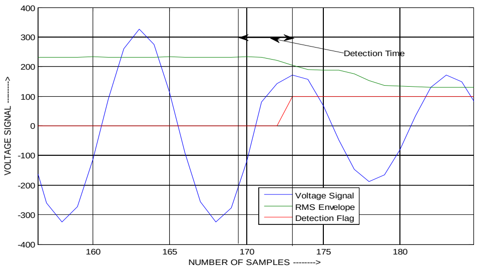

Fig 5: Voltage Sag Detection Using Full Cycle RMS Algorithm (110V Tapping& 500 Hz)

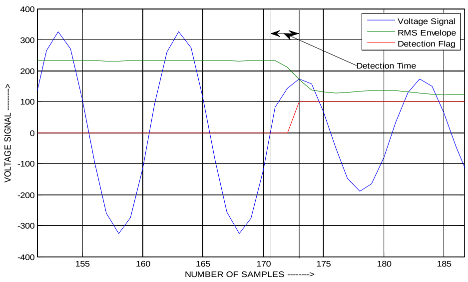

Fig 6: Voltage Sag Detection using Half Cycle RMS Algorithm (110V Tapping& 500 Hz)

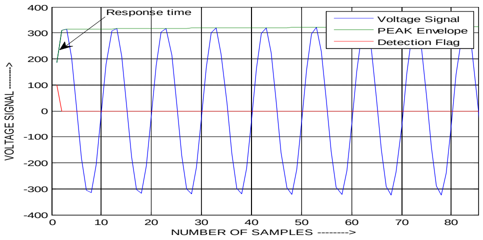

Fig 7: Voltage Sag Detection Using full Cycle peak Algorithm (110V Tapping& 500 Hz)

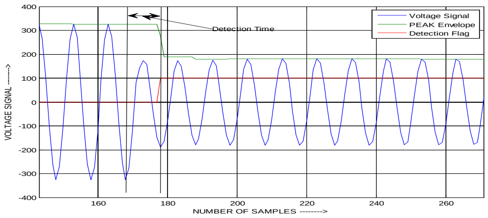

Fig 8: Voltage Sag Detection Using full Cycle peak Algorithm (110V Tapping& 500 Hz)

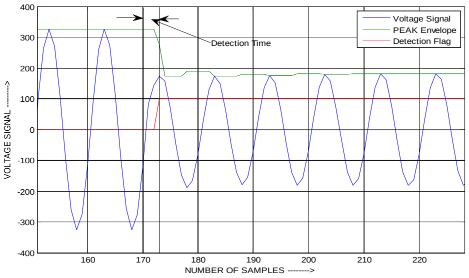

Fig 9: Voltage Sag Detection Using Half Cycle peak Algorithm (110V Tapping& 500 Hz)

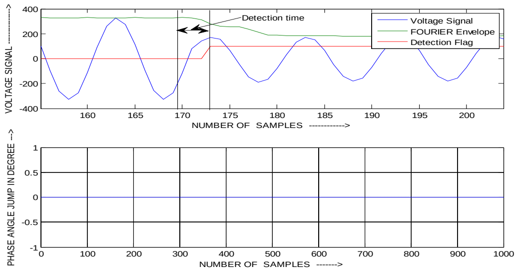

Fig 10: Voltage Sag Detection using Full Cycle Fourier Algorithm (110V Tapping& 500 Hz)

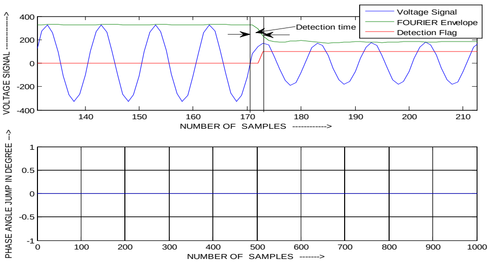

Fig 11: Voltage Sag Detection using half Cycle Fourier Algorithm (110V Tapping& 500 Hz)

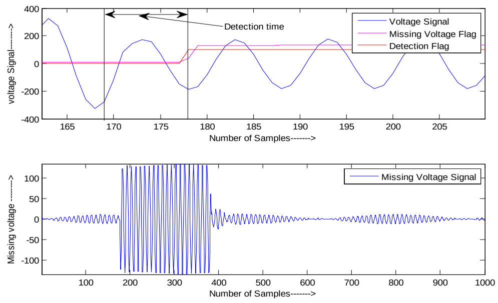

Fig 12: Voltage Sag Detection using Full Cycle Missing Algorithm (110V Tapping& 500 Hz)

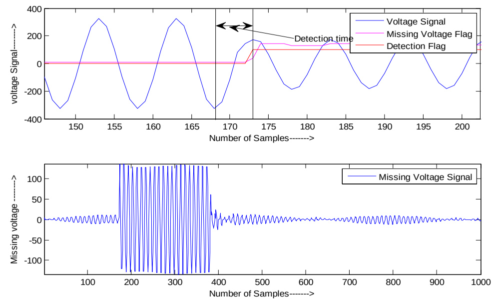

Fig 13: Voltage Sag Detection using Half Cycle Missing Algorithm (110V Tapping& 500 Hz)

- Figure 5 shows the voltage sag detection using full cycle RMS window algorithm (110V Tapping). It can observe that the transition period of the voltage sag event consist of five samples for full cycle window algorithm. Thus the detection time of 10ms is obtained for the sampling frequency of 500 Hz.
- Figure 6 shows voltage sag detection using half cycle RMS algorithm. It can observe that the transition period of the voltage sag event consist of 2 samples for half cycle window algorithm. Thus the detection period of 4ms is obtained for the sampling frequency of 500 Hz..
- From figure 7, it can be seen that, peak value detection method has fast response time. It can detect the peak within the quarter cycle, but peak method requires more detection time than the RMS and Fourier method.
- Such kind of observation is carried out for results of Peak, Fourier transform and Missing Voltage Method from the fig. 8 to 13 for both full cycle and half cycle window method. The summary of those results are shown in table 1 and 2.
- Referring to table 1, it can be observed that detection time for RMS and Fourier transform Method is same irrespective of window length.
- Again from table 1, peak value method requires the more detection time than the RMS and Fourier transform algorithm, because once the peak value is detected by the peak algorithm it will hold for complete window.

Table 1 Voltage Sag Detection Time (110V Tapping).

	Full Cycle Window			Half Cycle Window			
Method	Detection Time (ms)	Depth of sag (%)	Duration of sag (cycles)	Detection Time (ms)	Depth of sag (%)	Duration of sag (cycles)	Sampling Frequency (Hz)
RMS METHOD	10	54.6699	22.3000	4	53.0322	21.4000	500
PEAK METHOD	20	53.8916	20.7000	5	53.0125	21.2000	500
FOURIER METHOD	10	54.6779	22.3000	4	53.0641	21.5000	500
MISSING VOLTAGE METHOD	18	56.7818	20.7000	8	55.9034	21.2000	500

Table 2 Voltage Sag Detection Time (110V Tapping).
For different sampling frequencies

	Full Cycle Window			Half Cycle Window			
Method	Detection Time (ms)	Depth of sag (%)	Duration of sag (cycles)	Detection Time (ms)	Depth of sag (%)	Duration of sag (cycles)	Sampling Frequency (Hz)
RMS METHOD	7	50.0827	26.8500	4	48.6708	26.1500	1 KHz
PEAK METHOD	18	51.6923	25.3500	7	49.2308	25.8500	1 KHz
FOURIER METHOD	6	50.0655	26.7500	4	48.6665	26.1500	1 KHz
MISSING VOLTAGE METHOD	18	52.0397	25.3500	8	49.5802	25.8500	1 KHz
RMS METHOD	6.4	50.6819	10.0700	3.6	48.5744	9.7100	5KHz
PEAK METHOD	19	51.6923	8.5500	9	50.4615	9.0500	5KHz
FOURIER METHOD	7	49.9400	10.4000	3.4	47.4747	9.7800	5 KHz
MISSING VOLTAGE METHOD	18.2	52.0397	8.5400	8.6	50.8100	9.0400	5 KHz
RMS METHOD	5.8	50.6386	8.6950	2.6	49.5310	7.9650	10 KHz
PEAK METHOD	20	51.6923	6.8950	10	49.2308	7.3950	10 KHz
FOURIER METHOD	6.4	50.6321	8.7150	4	49.5385	7.9700	10 KHz
MISSING VOLTAGE METHOD	17.2	52.0397	6.8900	9.8	49.5802	7.3900	10 KHz

- The difference in detection time of RMS and Peak full cycle algorithm is 10ms and for half cycle algorithm this difference is 1ms.

- From table 1, Missing voltage method takes maximum detection time as it requires either RMS or Peak method to calculate the missing voltage. Its detection time for full cycle is 18ms and half cycle is 8ms. As compared to RMS or Fourier algorithm the difference in detection time is 8ms and 4ms for full cycle and half cycle window respectively. The difference in detection time of peak and missing voltage method is 2ms and 3ms for full cycle and half cycle window respectively. That means the half cycle peak algorithm. give faster detection than the half cycle missing voltage algorithm.
- From the table 2 shows that the voltage sag detection time for different sampling frequencies such as 1KHz, 5KHz and 10KHz. The voltage sag event consist of seven samples for full cycle window algorithm. Thus the detection period of 7ms is obtained for the sampling frequency of 1 KHz.
- Figure 14 shows the voltage sag detection using full cycle RMS window algorithm (110V Tapping & 1 KHz). It can Thus the detection time of 7ms is obtained for the sampling frequency of 1 KHz.
- Figure 15 shows voltage sag detection using half cycle RMS algorithm. It can observe that the transition period of the voltage sag event consist of four samples for half cycle window algorithm. Thus the detection time of 4 ms is obtained for the sampling frequency of 1 KHz.
- Figure 16 and figure 17 shows the voltage sag detection using full cycle and half cycle RMS algorithm (110V Tapping & 5 KHz)
- Figure 18 and figure 19 shows the voltage sag detection using full cycle and half cycle RMS algorithm (110V Tapping & 10 KHz).

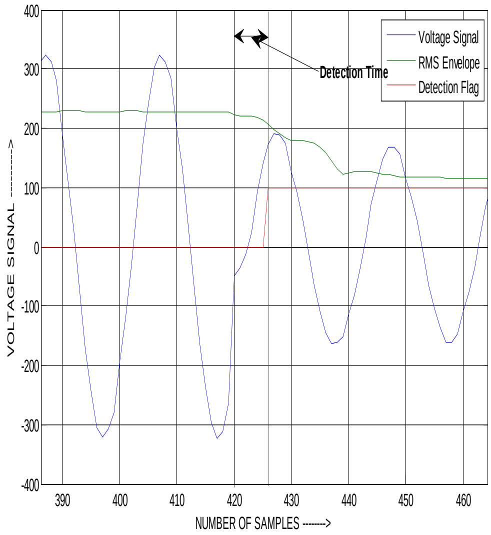

Fig 14: Voltage Sag Detection using Full Cycle RMS Algorithm (110V Tapping& 1 KHz)

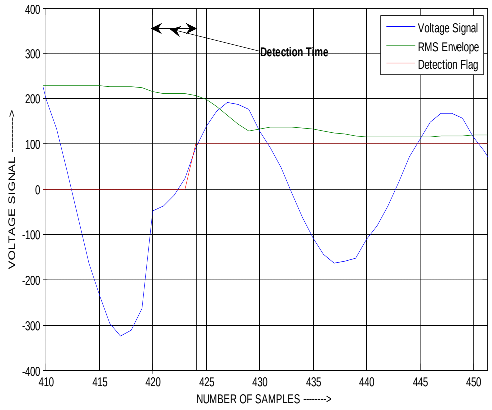

Fig 15: Voltage Sag Detection using Half Cycle RMS Algorithm (110V Tapping& 1 KHz)

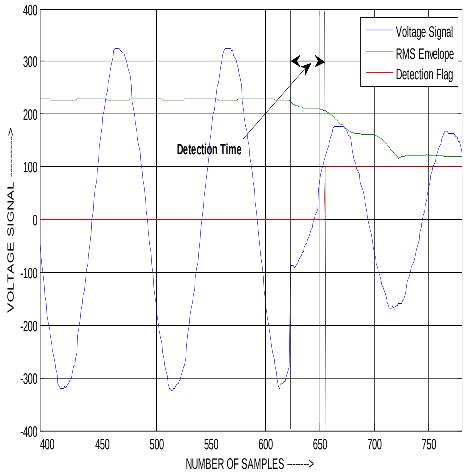

Fig 16: Voltage Sag Detection using Full Cycle RMS Algorithm (110V Tapping& 5 KHz)

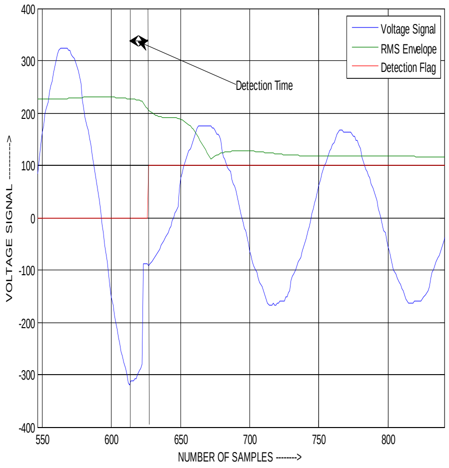

Fig 17: Voltage Sag Detection using Half Cycle RMS Algorithm (110V Tapping& 5 KHz)

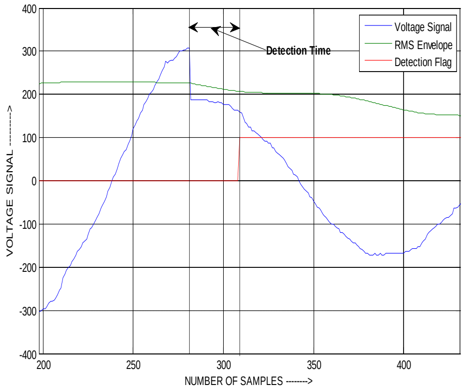

Fig 18: Voltage Sag Detection using full Cycle RMS Algorithm (110V Tapping& 10 KHz)

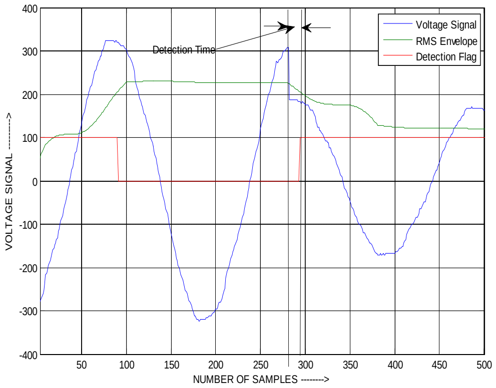

Fig 19: Voltage Sag Detection using Half Cycle RMS Algorithm (110V Tapping& 10 KHz)

- It can observe that from table 2 as the sampling frequency increases the detection time reduces. The minimum detection time of 5.8ms for full cycle and 2.6ms for half cycle RMS algorithm at 10 KHz sampling frequency obtained.
- The detection time of Peak, Fourier and Missing Voltage algorithm at different sampling frequency such as 1KHz, 5 KHz, 10 KHz is shown in table 2, it can observed that the half cycle window give more accurate sag depth than the full cycle window.

As per as quantification of sag or swell is concerned, most important parameter is the magnitude (depth) of the voltage sag or swell. The magnitude and Duration of voltage sag is also shown in table 1 and 2. The magnitude is expressed in percentage and duration is given in cycle (according to definition of voltage sag). The meaning of 110V tapping is that the RMS voltage reduced from the nominal voltage (230V). When the sag event of 110V tapping is created the voltage reduces to 120V. Then the magnitude of sag is calculated as (120/230), which is equal to 52.17%. The magnitude of the sag obtained from the algorithms is between 53 to 56%, the difference is due to variation in the instantaneous voltages.

5.2 Discussions On Voltage Swell

The offline analysis results of all four methods for detection of voltage swell is presented below-

5.2.1 Analysis using full cycle and half cycle Window length

For analysis of voltage swell using proposed four detection methods, the swell is created by changing tap of transformer from nominal voltage to 40V tap above nominal voltage in online condition. The analysis results are discussed below-

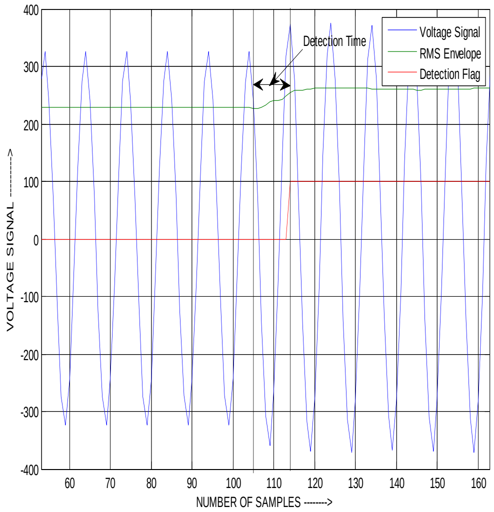

Fig 20: Voltage Swell Detection using Full Cycle RMS Algorithm (40V Tapping)

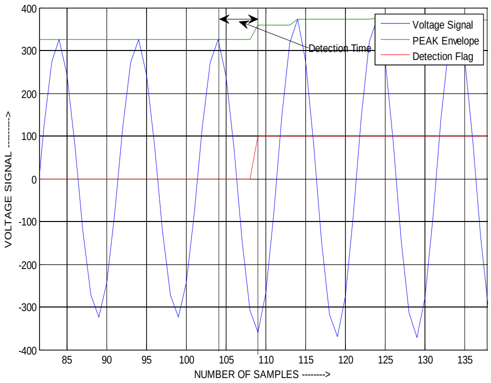

Fig 21: Voltage Swell Detection using Full Cycle Peak Algorithm (40V Tapping)

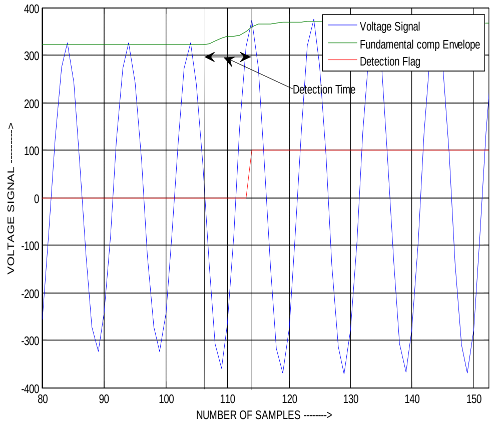

Fig 22: Voltage Swell Detection using full Cycle Fourier Algorithm (40V Tapping)

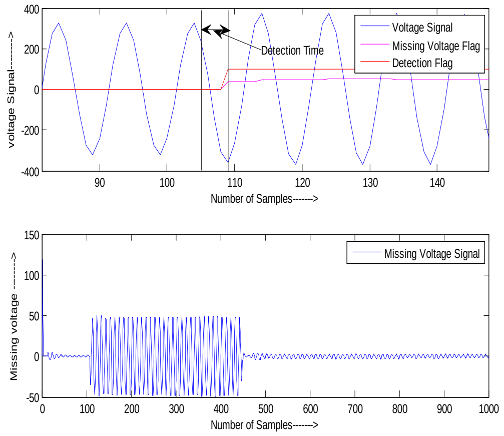

Fig 23: Voltage Swell Detection Using Full Cycle Missing Algorithm (40V Tapping)

Table 3 Voltage Swell Detection Time (40V Tapping)

Method	Full Cycle Window			HalfCycle Window			Sampling Frequency (Hz)
	Detection Time (ms)	Depth of sag (%)	Duration of sag (cycles)	Detection Time (ms)	Depth of sag (%)	Duration of sag (cycles)	
RMS METHOD	10	54.6699	22.3000	4	53.0322	21.4000	500
PEAK METHOD	20	53.8916	20.7000	5	53.0125	21.2000	500
FOURIER METHOD	10	54.6779	22.3000	4	53.0641	21.5000	500
MISSING VOLTAGE METHOD	18	56.7818	20.7000	8	55.9034	21.2000	500

- Fig 20, 21, 22 and Fig 23 shows the voltage swell detection using full cycle RMS, Peak, Fourier Transform & Missing voltage algorithm respectively (40V nominal voltage Tapping).
- Fig 24, 25, 26 and Fig 27 shows the voltage swell detection using half cycle RMS, Peak, Fourier Transform & Missing voltage algorithm respectively (40V above nominal voltage Tapping). Detection time of various methods for full cycle and half cycle window are given in table 3.
- The quantification of voltage swell is also shown in table 3.The magnitude and duration of voltage swell is shown. It is expressed in percentage and cycles. The difference in magnitude of voltage swell obtained from full cycle and half cycle algorithm for all methods is approximately 1volt, which is negligible.
- Duration of voltage swell in number of cycles obtained from both half and full cycle algorithm for all methods is approximately same.
- Fourier transform algorithm provides minimum detection of 10 ms for full cycle window length.

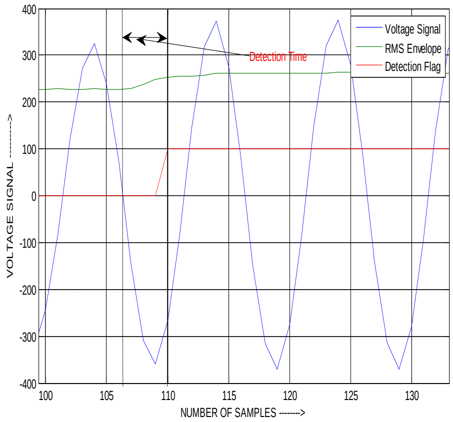

Fig 24: Voltage Swell Detection using Half Cycle RMS Algorithm (40V Tapping)

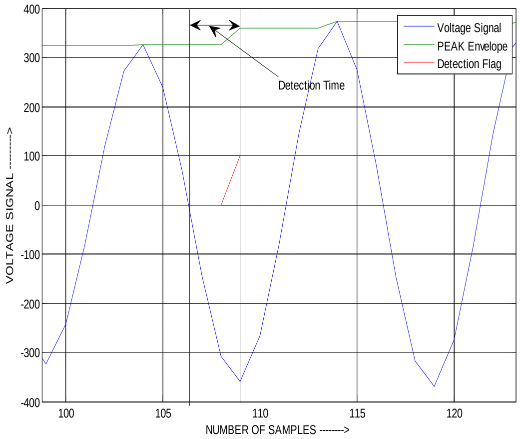

Fig 25: Voltage Swell Detection using Half Cycle Peak Algorithm (40V Tapping)

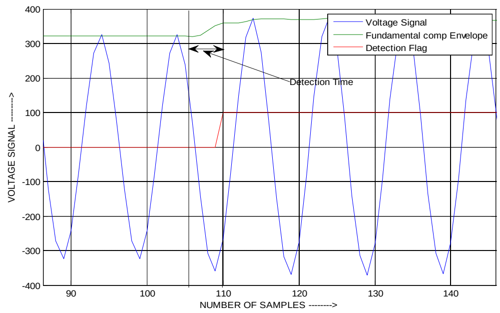

Fig 26: Voltage Swell Detection using Half Cycle Fourier Algorithm (40V Tapping)

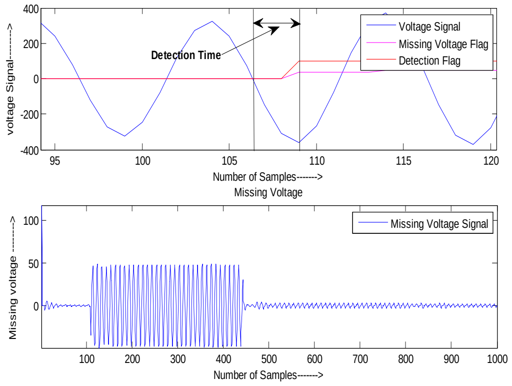

Fig 27: Voltage Swell Detection using Half Cycle Missing Voltage Algorithm (40V Tapping)

5.3 Efect Of Sampling Frequency On Estimation Of Detection Time, Depth And Duration Of Voltage Sag:

The experimentation study was carried out for observing the effect of sampling frequency on quantification parameters and detection time of voltage sag by all proposed methods for the case considered (110V Tapping & sampling frequency of 500 Hz, 1kHz, 5kHz, 10kHz,).

- Table 1 and 2 shows that the detection time of RMS method for full cycle and half cycle window algorithms are 10ms and 4ms at 500 Hz, 7ms and 4ms at 1 KHz, 6.4 ms and 3.6ms at 5 KHz, 5.8ms and 2.6ms at 10 KHz. Therefore, as the sampling frequency increases the detection time reduces. The minimum detection time of 2.6 ms is achieved at 10 kHz sampling frequency for RMS method for half cycle algorithm.
- The missing voltage method requires desired voltage signal (Vref) and actual voltage sag signal in phase. This method requires help of RMS or Peak method for calculation of missing voltage..

5.4 Online Monitoring Of Voltage Sag And Swell

Online monitoring system for voltage sag and swell is developed in the laboratory using the hardware mentioned in section IV and PC. Online algorithms developed for each method provides the flag indication for the voltage sag or swell, signal envelop and stores the signals only under voltage sag and swell events. The snapshots of the online monitoring systems under events are given in figure 28 to figure 36.

Figure 28 shows captured voltage sag due to Induction Motor Starting using RMS Algorithm.

Similar results of online detection of voltage sag and swell using RMS, Peak, Fourier transform, and missing voltage algorithm is shown in fig 29 to fig 36.

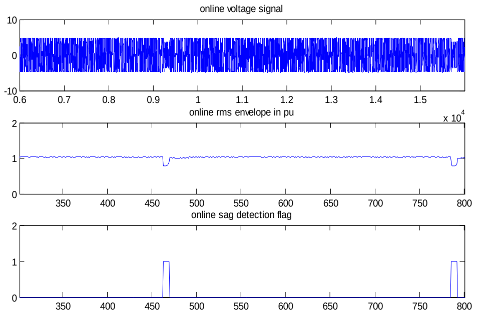

Fig 28: Online Detection of Voltage Sag Due to Induction Motor Starting using RMS Algorithm

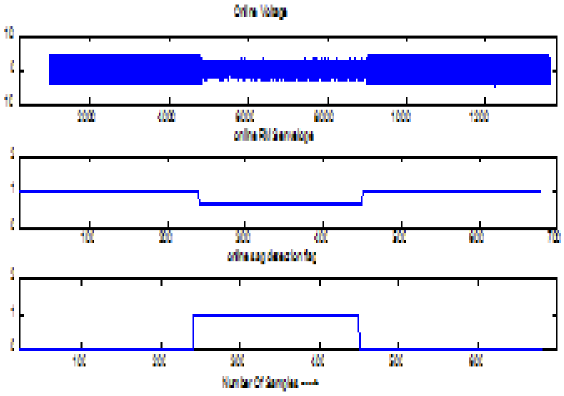

Fig 29: Online Detection of Voltage Sag using RMS Algorithm.

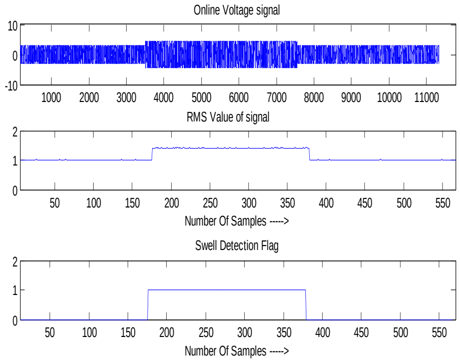

Fig 30: Online Detection of Voltage Swell using RMS Algorithm.

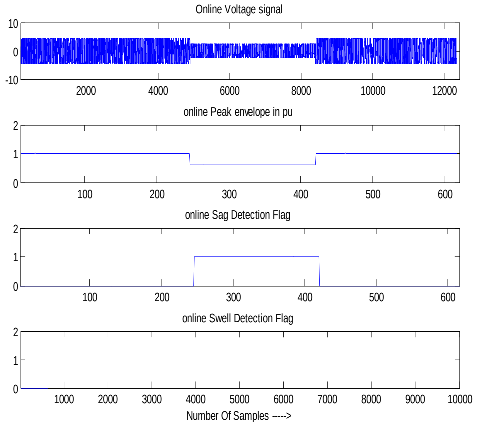

Fig 31: Online Detection of Voltage Sag using Peak Algorithm.

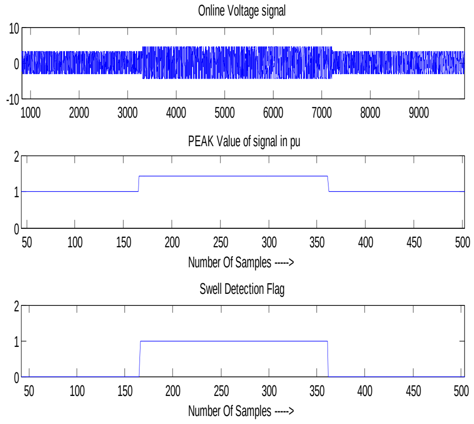

Fig 32: Online Detection of Voltage Swell using Peak Algorithm

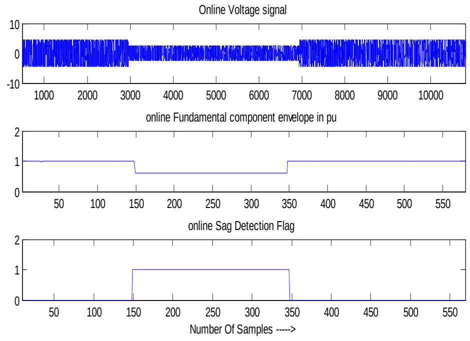

Fig 33: Online Detection of Voltage Sag using Fourier Algorithm.

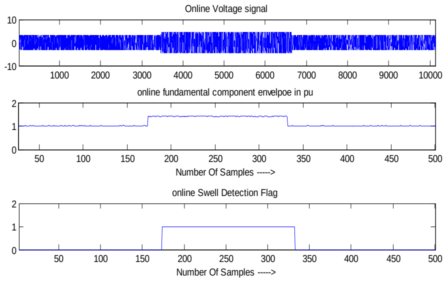

Fig 34: Online Detection of Voltage Swell using Fourier Algorithm.

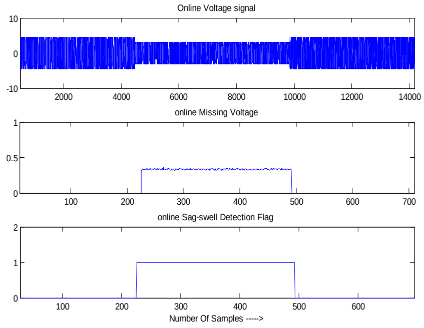

Fig 35: Online Detection of Voltage Sag using Missing Voltage Algorithm.

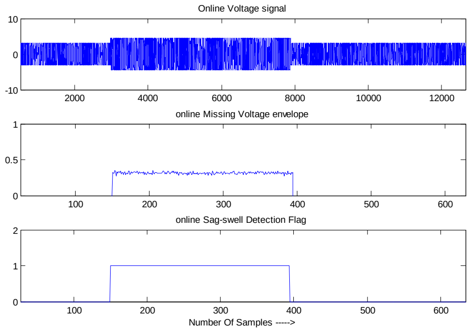

Fig 36: Online Detection of Voltage Swell using Missing Voltage Algorithm

VI. CONCLUSIONS

In this paper, the offline and online detection of voltage sag and swell is carried out using RMS, Peak, Fourier transform and Missing Voltage Methods.

It can be observed that RMS and Fourier method takes least detection time among the all method. Typical detection time for half cycle and full cycle algorithm are 4ms and 10ms respectively.

The result obtained from the RMS and Fourier Method is approximately same. The RMS method gives information about the magnitude and duration of voltage sag. Where, Fourier transform method gives the additional information regarding the phase angle jump.

The response time of RMS and Fourier Method is near to window length. While for Peak value algorithm response time is less i.e. peak is detected within the quarter cycle.

The Peak and Missing Voltage Method takes the largest detection time than RMS and Fourier Method.

The half cycle algorithm gives the faster detection than the full cycle algorithm.

t can be also observed that as the sampling frequency increases the detection time reduces.

It has been observed that, proposed methods does not provides the accurate detection time for lower depth voltage sag events.

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