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Comparative Analysis of Various Methodologies for Voltage Swell and Sag Detection in Online and Offline Conditions

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Abstract*:* *The fundamental voltage, current, and phase angle are required for a wide variety of power system applications. While detecting the sag and swell the important parameters required to be considered are their Magnitude, Duration and Phase Angle Jump. Various techniques use to detect voltage sag include: Root Mean Square (RMS), Fourier transform, Peak voltage detection and Missing voltage method. The problem with these methods is that they use a windowing technique and can therefore be too slow when applied to detect and mitigate voltage sags and swells since they use historical data. In this paper, the voltage sag and swell is detected using wavelet transform method, Root Mean Square (RMS), Fourier transform, Peak voltage detection and Missing voltage method. All these methods are compared on the basis of their, detection time, depth of the sag and sampling frequency. It is found that the wavelet transform is very powerful tool to detect voltage sag and swell. It gives accurate start and end detection time and duration of sag. All these methods are tested under offline and online conditions..*

Keywords: Power Quality (PQ), Fourier Transform (FT), Wavelet Transform.

I. INTRODUCTION

Power quality define as “any power problem manifested in voltage, current, or frequency deviations that results in failure or missed operation of utility or end user equipment”[11]

Until the 1960s 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 [13]. Over the last ten years, voltage sags have become one of the main topics concerning power quality among utilities, customers and equipment manufacturers.

The voltage sag is the most frequently occurring power quality disturbance than the voltage swell. 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. Hence the voltage sag occurs. because the energization period of large induction motors are of several minutes. 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.

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 1.8pu.

The voltage swells are usually associated with system fault conditions, but they are much less common than voltage sags. A swell can occur due to a single line-to-ground fault on the system resulting in a temporary voltage rise on the un-faulted phases. swells can also be caused by:

- switching off a large load
- switching on a large capacitor bank
- Single line to ground fault.

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

i. Root Mean Square (RMS)
ii. Peak Method
iii. Fourier Transform Method
iv. Missing Voltage Method
v. Wavelet Transform Method.

All these methods are tested under the offline condition and first four methods are tested under online condition to detect voltage sag. with these methods, we have detected sag due to induction motor energization and welding transformer energization at low voltage distribution level in online condition. These methods are compared based on their detection time, sampling frequency, half cycle and full cycle window algorithm.

Our observation is that still some distribution companies not give importance to power quality they simply distribute power to the consumers. The large magnitude voltage sag can be converted in to voltage interruptions for several hours. Due to this customers equipment may get damaged. So to avoid such problems these algorithms can be implemented practically.

II. EFFECTS OF VOLTAGE SAG

The effects 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.

EFFECTS OF VOLTAGE SAGS ON ADJUSTABLE SPEED DRIVES

Adjustable speed drives (ASD) are very susceptible to slight variation in voltages. The reason for their high susceptibility is the presence of power electronics components that are sensitive to voltage variation. When voltage sag occurs on to the system, the reduction in voltage at the input of the rectifier circuit causes the reduction in the dc voltage. To avoid damages of electronic components, protective systems shutdown the ASD. This causes stoppage of industrial process and this will causes huge financial losses.

EFFECT OF VOLTAGE SAGS ON INDUCTION MOTORS

Induction motors represent the most typical loads in power system applications. They consume about 60% of the electrical energy generated. The torque of induction motor is proportional to the square of the voltage. Thus the voltage sag is the prime cause of the induction motor stoppage. Thus disrupting the normal working, this leads to interruption in the processes and cause financial losses.[8] The basic observed effects of voltage sag on the induction motor are:

- Drop in speed
- Torque oscillations
- Over-current

EFFECTS OF VOLTAGE SAGS ON LIGHTING LOADS

Voltage sags may cause lamps to extinguish. Light bulbs will just twinkle; that will likely not be considered to be a serious effect. High pressure lamps may extinguish; it takes several minutes for them to re-ignite. All lamps, except incandescent lamps, require high voltage across the lamp electrodes during starting. This voltage is essential to initiate the arc. Traditionally, a choke coil is employed across the electrodes to produce high voltage pulses. The lamp starting voltage is affected to a large extent by the ambient temperature and humidity levels as well as the supply voltage.

Fluorescent lamps reach their full emission level immediately after ignition. High-pressure lamps need a few minutes to reach their full light output, while low-pressure lamps take up to 15 minutes for the same.

III. EFFECTS OF VOLTAGE SWELL

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 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.

IV. DETECTION METHODS

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 Method, Fourier Transform Method, Missing Voltage Method and wavelet transform Method.

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.

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. The RMS value can be calculated as

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

Where, N is Number of the samples per cycle

V (j) is jth sample of the recorded voltage waveform

VRMS(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. [14]

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. In order to spend less processing time, a recursive alternative can be used. This provides a significant processing time saving when N is large.

PEAK METHOD

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

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

Where, Vpeak = peak value of voltage signal.

V (t) = the sampled voltage waveform.

T= is an integer multiple of one half cycle or Full cycle.

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

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

$$V_{fund} = \frac{2}{N} \sum_{n=-\infty}^{\infty} V(n) e^{(-jw_0 n)} \tag{3}$$

Where, W0= 2π (f/Fs). f=frequency of supply.
Fs=sampling frequency. V (n) = sampled voltage waveform; N=Number of sample in one cycle;
Vfund= 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);

MISSING VOLTAGE METHOD

The missing voltage is defined as the difference between the desired instantaneous voltage and the actual instantaneous one [2]. The missing voltage is calculated from the following expression.

$$Vpll\ (t) = A \sin(wt - \Phi a) \tag{4}$$

$$Vsag\ (t) = B \sin(wt - \Phi b) \tag{5}$$

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

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

$$m\ (t) = R \sin(wt - \Psi) \tag{8}$$

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 presag and sag voltages A and B are always in phase.

WAVELET TRANSFORM METHOD

In recent years, researchers in applied mathematics and signal processing have developed powerful wavelet techniques for the multiscale representation and analysis of Signals These new methods differ from the traditional Fourier techniques Wavelets localize the information in the time-frequency plane; in particular, they are capable of trading one type of resolution for another, which makes them especially suitable for the analysis of non-stationary signals. One important area of application where these properties have been found to be relevant is power engineering. Due to the wide variety of signals and problems encountered in power engineering, there are various applications of wavelet transform. These range from the analysis of the power quality disturbance signals to, very recently, power system relaying and protection.

The DWT analyzes the signal at different frequency bands with different resolutions by decomposing the signal into a coarse approximation and detail information. DWT employs two sets of functions, called scaling functions and wavelet functions, which are associated with low pass and high pass filters, respectively. The decomposition of the signal into different frequency bands is simply obtained by successive high pass and low pass filtering of the time domain signal. The original signal x[n] is first passed through a half band high pass filter g[n] and a low pass filter h[n]. After the filtering, half of the samples can be eliminated according to the Nyquist's rule, since the signal now has a highest frequency of π /2 radians instead of π . The signal can therefore be sub sampled by 2, simply by discarding every other sample. This constitutes one level of decomposition and can mathematically be expressed as follows:

$$y_{high}(k) = \sum_n x(n).g(2n-n) \tag{9}$$

$$y_{low}(k) = \sum_n x(n)h(2k-n) \tag{10}$$

where yhigh[k] and ylow[k] are the outputs of the high pass and low pass filters, respectively, after sub sampling by 2.

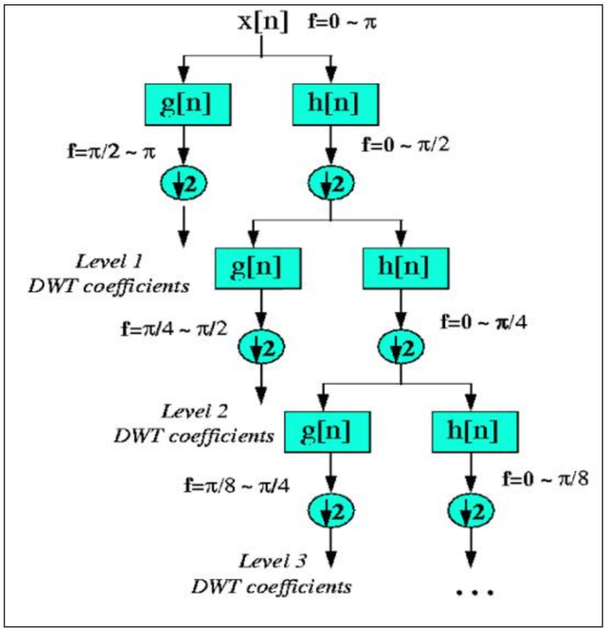

Fig. 1 Decomposition diagram

V. EXPERIMENTAL SETUP

Figure 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, and personnel computer.

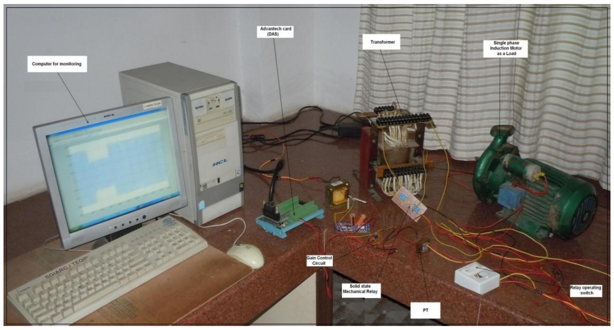

Fig 2: Practical Experimental setup of the system

Single phase Transformer:

In experimentation, single phase 2KVA, 230V/230V, isolation transformer is used. It has taps that can be set from 0 V to 230 V in steps of 10 V. Change of taps can be viewed as voltage sag or swell conditions for online simulation.

Solid State Mechanical Relay

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 of 230V/10A and the operating coil of the relay is provided with the +12V DC supply. than nominal voltage, to get required amount of swell magnitude. The No contact is connected to the 100% rated voltage tapping of transformer.

Induction Motor

Single phase induction motor of 2hp is used to simulate the voltage sag occurring due to the inrush currents.

Potential Transformer

A step down transformer of 230/6v is used as potential transformer to provide the signal of desired magnitude for the measurement purpose

Advantech Data acquisition Card

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.

Gain control circuit

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. A simple closed loop op-amplifier used as an inverting amplifier as shown in fig 3

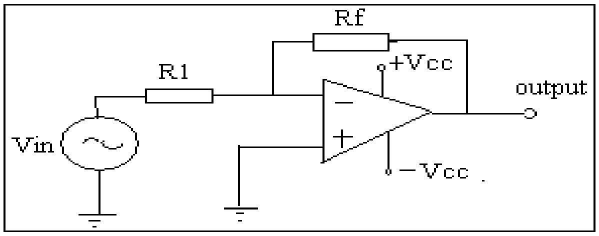

Fig 3: Inverting amplifier as a gain control circuit.

The output of the inverting amplifier is given as

$$V_{(0)} = -\frac{Rf}{R1}Vin$$

Where, Rf= Feedback Resistor, Rin= Input Resistor.

Gain=A=Rf/R1. Vin=Input Voltage.

V (0) =Output Voltage of op-amplifier.

The gain 0.5 is achieve by choosing the values of Rf =5kΩ and R1=10kΩ. The input voltage at the op-amplifier is 6V and voltage available at the output is 3V.

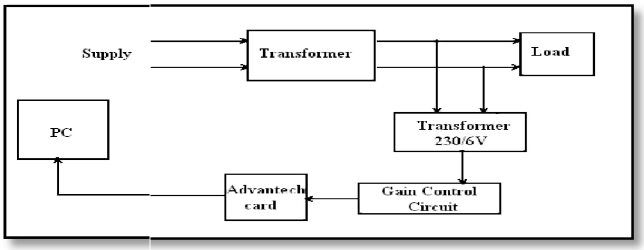

Fig 4 Block Diagram of Practical Experimental Setup

VI. RESULTS AND DISCUSSION

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.

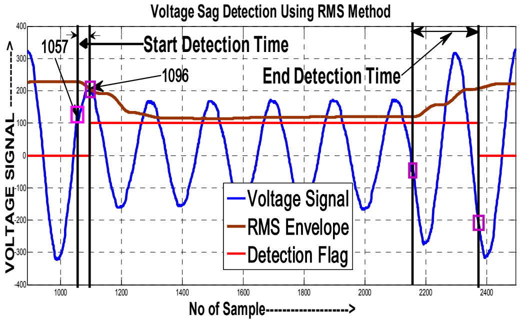

Fig 5 voltage sag detection using RMS Method (10 khz)

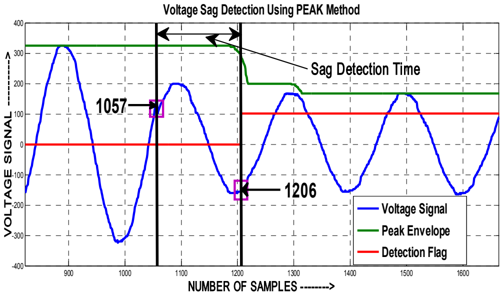

Fig 6 voltage sag detection using Peak Method

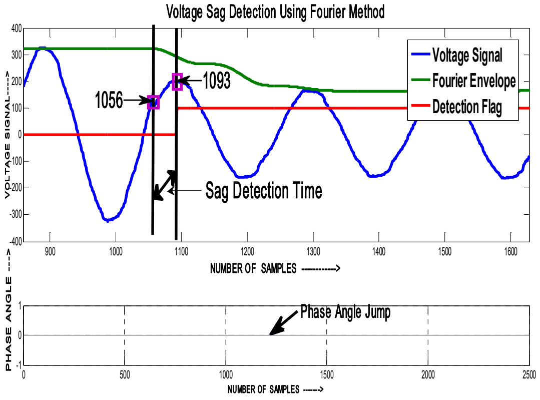

Fig 7 Voltage sag detection using Fourier Transformed Method.

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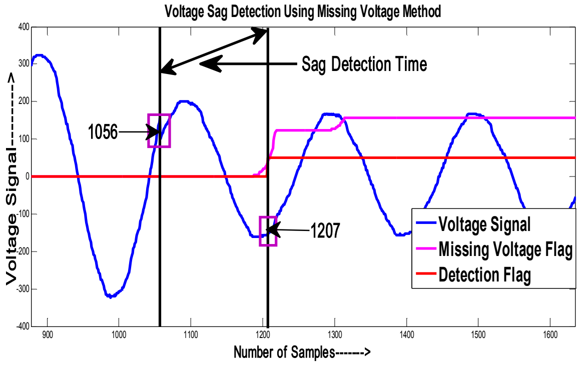

Fig 8 Voltage Sag Detection Using Missing Voltage Method

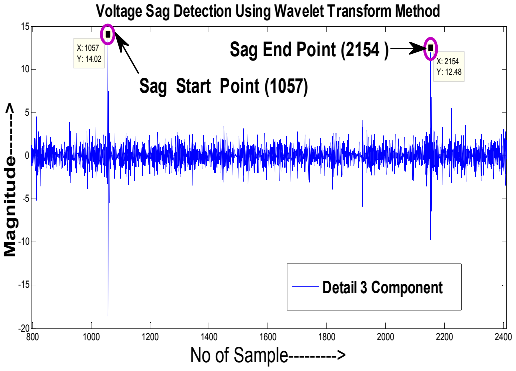

Fig 9 Voltage Sag Detection Using Wavelet Transformed Method.

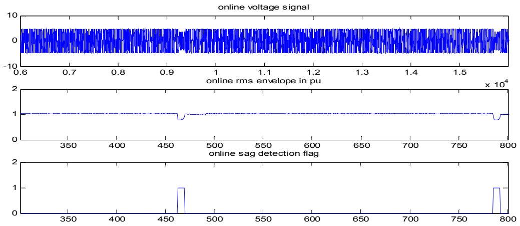

Fig 10 Online Detection of Voltage Sag Due to Induction Motor Starting using RMS Algorithm.

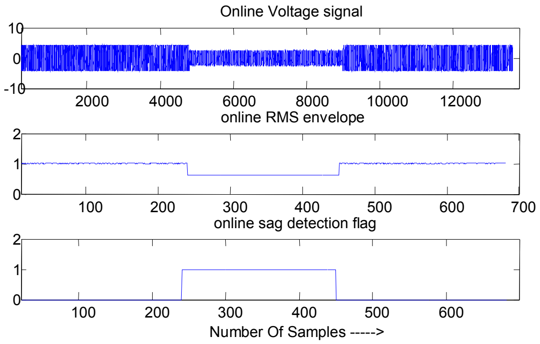

Fig 11 Online Detection of Voltage Sag using RMS Algorithm.

In this paper only results of voltage sag signal capured at sampling frequency of 10Khz has been showed. The result of voltage sag of 500Hz,1KHz,5KHz are shown in table 1.1

Table 1.1 Voltage Sag Detection Time

	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)	Samplin Frequen (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
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 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. The figure 5 shows the result of voltage sag detection using RMS method with sampling frequency of 10khz. It observes that the voltage sag is detected at start by 5.8ms using full cycle algorithm & 2.6 ms for half cycle algorithm. These are the minimum detection time observed for RMS and Fourier Method. The end point of voltage sag also not accurately detected by the all these algorithms excepting Wavelet transform method. There is delayed in detection of end point due to the windowing technique. Hence voltage sag duration is not accurately detected by these methods.

So the problems associated with the windowing methods can be resolved by the Wavelet Transformed Method. From figure 9, the initiation of voltage sag at samples no 1057 and end of voltage sag at sample no 2154 respectively as shown in figure 9. Thus voltage sag or swell can be detected at exact point of initiation there is no delay while detection at start and end point.

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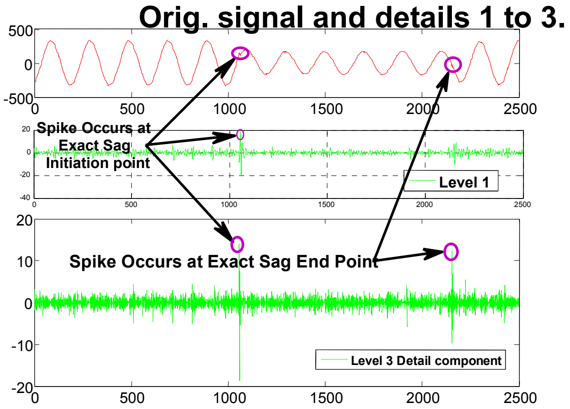

Figure 12 Voltage Sag Detection Using Wavelet Transfomed Method (Detail 3 component)

The all cadidate wavelet are applied to the all test result it is found that db13 gives the best results amongs the all family of wavelet. The better spikes can be obtained at decomposition level 3 as shown in figure 12.

The results of online detection of voltage sag using RMS method as shown in figure 12. Also we have detected the voltage sag online due to induction motor starting as shown in figure 10.

VII. CONCLUSION

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. The offline detection of voltage sag using wavelet transformed method also carried out. 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.

It is observed that as the sampling frequency increases the detection time reduces. The typical least detection time obtained among the all method at 10 KHz sampling frequency for half and full cycle RMS algorithm are 3.3ms and 5.8 ms respectively. It has been observed that, proposed methods does not provides the accurate detection time for lower depth voltage sag events.

At last the wavelet transformed method is superior over the other method. It gives accurate sag initiation point and sag end point. This information is very useful while mitigating the voltage sag. The delay in sag detection is completely minimized. Thus wavelet transform gives the exact duration of voltage sag/swell.

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