BASIC ANALYSIS TOOLS FOR POWER TRANSIENT WAVEFORMS

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ABSTRACT

In this study, basic analysis tools for power transients waveforms are discussed and new tools are introduced. General analysis tools for power transient waveforms are introduced. Problems and limitations associated with the RMS and Fourier transform techniques are discussed. A new analysis tool is proposed, namely "Missing Voltage Technique", and a brief detail is given. Newly emerging techniques of Wavelet transform techniques are also briefly introduced.

I. INTRODUCTION

Power transients are common occurrences in modern power systems. In other cases, natural and man-made events such as faults or insulator flashovers due to animals, trees, wind, automobile accidents, and lightning may cause a temporary magnitude reduction of the voltage on one or more phases. [1-3].

AC voltage and current measurements are often made to determine the amount of power available for operating equipment. Therefore, sag voltages are usually expressed in terms of RMS. However, with an RMS computation, the phase and polarity information is lost because RMS uses only the absolute magnitude of the signal. The RMS value is based on the averaging of previously sampled data for one cycle (for 60 Hz power frequency: 1/60=16.67ms). Therefore, it represents one cycle historical average value, not the momentary or instantaneous reading [4].

Voltage sags are usually characterized by the amplitude in RMS and the duration. Most of the times, this kind of assessment ignores the so called phase angle shifts associated with the voltage sag, the point-on-wave of fault initiation, and the nonstationary nature of some sags, e.i. non-rectangular shape of RMS value of voltage sags. Phase angle shifts or in short phase shifts may cause mal-function, tripping of the device, or even damage the equipment, depending on the type of electronic equipment, its settings, loading, rating, device protection philosophy etc. The most likely sensitive devices seem to be the power electronic converters which relies on the correct zero crossings of the supply voltage, such as DC drives, static VAR compensators, etc [5-8].

Power system transient waveforms are typically non-periodic signals which may contain both high-frequency and low-frequency oscillations and localized impulses superimposed on the power frequency. Fig. 1 shows an example of three-phase waveforms of capacitor switching voltage transients. These characteristics present a problem for traditional Fourier analysis because it assumes a periodic signal and also a wide-band signal requires more dense sampling and longer time periods to maintain good resolution in low frequencies.

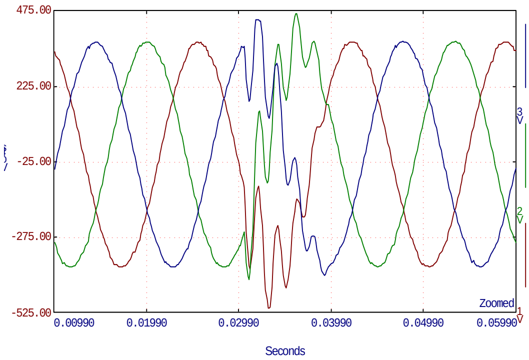

Fig. 1 Waveform of three-phase voltage transients.

In this study, new techniques which are named as “Missing Voltage Technique” and “Wavelet Analysis Technique” are proposed.

II. ANALYSIS TOOLS FOR POWER TRANSIENT WAVEFORMS

2.1 RMS Calculation Technique: In an effort to determine a single numerical value to quantify a time-varying sinusoidal voltage and current, a relationship was developed between a DC and a periodic quantity that would result in each delivering the same power to a resistive load. Hence the effective value or Root Mean

Square (RMS) gives the equivalent value of a DC supply that would give the same power dissipation in a resistive load. For a continuous periodic signal v(t), the RMS value is defined as

$$V_{RMS} = \sqrt{\frac{1}{T}\int_{t_0}^{t_0+T} v^2(t)dt} \qquad (1)$$

where T is the period of the signal.

In equation (1), the RMS value loses its conventional meaning if the period T is lost or the period is less than a half cycle of the measured signal. Since most waveform data is in digital format, the integration in equation (1) is replaced by a summation for discrete-time signals,

$$V_{RMS} = \sqrt{\frac{1}{N}\sum_{n=0}^{N-1} v^2[n]} \qquad (2)$$

where N is the total number of samples in one period.

The widely-used moving-window RMS value is calculated for digitally recorded data as follows. 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 put on the leading edge of the RMS magnitude-time scale. Since a waveform disturbance is not stationary, the window is moved one data point to the right and the oldest data (at the left of the window) is dropped as time progresses with each increment. As an example, with a sampling rate of 15360 Hz, one cycle contains 256 samples. So, each of the 256 samples in the window is squared, summed together, and averaged over the total number of samples in the window (256). The window size always remains the same (i.e., the number of samples within a window is always 256).

For example, Fig. 2 (a) shows the case of an ideal voltage sag where the transition takes place on the zero-crossing and there is no distortion during the sag. This voltage sag has a remaining magnitude of 50% of the nominal and has a duration of 6-cycles. (Note that this plot has been normalized.)

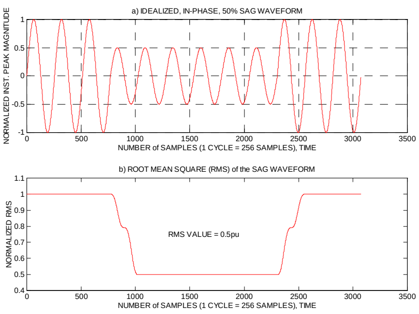

Fig. 2 (a) Idealized, in-phase sag, (b) Its RMS value.

By employing the moving-window RMS computation technique, Fig. 2 (b) is obtained. It is clear by examination of Fig. 2 (a) that the sag has about 6-cycle steady-state duration and has a depth of 50%. The transition to the sag is sharp (at the zero crossing) and recovery is sharp as well. RMS plot shows a one-cycle transition before reaching the 0.5 pu value and a one-cycle rise to recovery. This slow transition is due to the moving window retaining almost one cycle of "historical" information in the calculation. Thus the duration of the sag is in error by almost one cycle since the sag appears to have a duration of almost 7 cycles if one examines only the RMS plot. Furthermore, the point on wave of initiation and recovery of the sag is not clear.

The failure of the RMS value to adequately characterize a voltage sag with a phase shift is demonstrated in the next example. A sag measured from a line-to-line fault lasting 6 cycles is shown in Fig 3 (a). The line-to-line fault results in almost 60^0 phase shift in both phases b and c. By examination of this event, it is clear that the moving-window RMS calculation reveals a sag of 0.5 pu with a duration of about 6 cycles. The error in estimation will be clearly be understood in the next analysis which is Phasor.

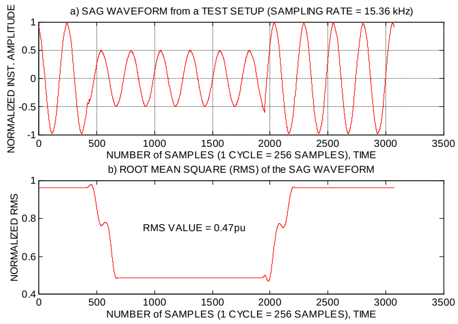

Fig. 3 (a) 60^0 Phase-shifted sag from a test, (b) Its RMS value. Both normalized to peak=1.0 pu.

2.2 Phasor Analysis Technique: In the study of sinusoidal quantities, one is interested in the frequency, the amplitude, and the phase angle, usually in relation to other sinusoidal quantities. One can think of a sinusoidal wave with an amplitude and phase angle as a rotating vector with a certain angular frequency. These rotating vectors, which are employed to represent the time variation of sinusoidal quantities, are called phasors.

The phasor representation of the voltage sag in Fig. 3(a) is easily visualized since the voltage waveforms are sinusoidally shaped. Fig. 4 shows the PLL voltage, sag voltage and the missing (required injection) voltage of the previous sag waveform. Here three concentric circles show the various magnitude levels and the phase sequence is abc. The phasor representation shows the event in steady-state as the faulted phases being b' and c'. When the sag hits phase b and c, the magnitude is reduced to b' and c' level (for about 6 cycles.) The missing voltage is the dashed-vector of 0.83 pu magnitude between the tips of b' to b, and c to c' phasors.

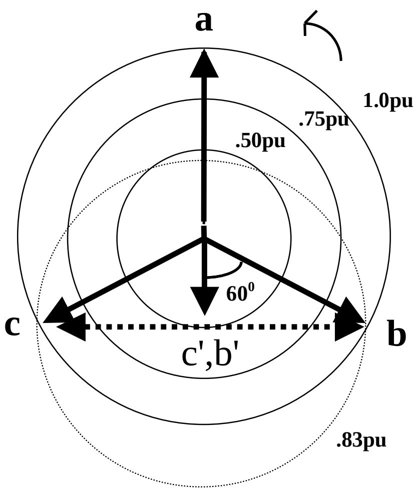

Fig. 4 Phasor diagram of the sag in Fig. 3 (a).

However, whenever the sine-waveshape and periodicity is lost, or the frequency of the waveform become nonstationary, one cannot make use of the phasor analysis.

2.3 Fourier Analysis Technique: The Fourier Transform of a continuous-time signal x(t), X(f), is given by

$$X(f) = \int_{-\infty}^{+\infty} x(t)e^{-j2\pi ft}dt \qquad (3)$$

The continuous function X(f) is the frequency-domain representation of x(t) obtained by summation of an infinite number of complex exponentials. The Discrete Fourier Transform (DFT) is used to find X(f) on a digital computer with discrete (sampled) and finite-length (time-limited) signals. It is defined by

$$X[k] = \sum_{n=0}^{n=N-1} x[n]e^{-\frac{j2\pi kn}{N}} \qquad (4)$$

where x[n] is a sequence obtained by sampling the continuous time signal x(t) every T_s seconds for N samples. Two important requirements to using the DFT are conformity with the Nyquist Criterion and the requirement that x[n] be periodic. Fig. 5 (a) shows an actual voltage sag waveform. Horizontal line shows the time as 256 points in one 60 Hz cycle, i.e. 256 points corresponding 16.66 ms (one period). DFT of the whole waveform shows a 60Hz fundamental component as the dominant and then a spread spectrum of a few hundred Hz without much significant magnitude (Fig. 5 (b)-(c)). It is difficult to see the effect of voltage sag on the frequency spectrum.

The Short-Time Fourier Transform (STFT) has been developed to reduce the effect of non-periodic signals on the DFT. STFT assumes local periodicity within a continuously translated time window. The STFT is similar to the Fourier Transform except that the input signal x(t) is multiplied by a window function ω (t) whose position is translated in time by τ ;

$$STFT(f,t) = \int_{-\infty}^{+\infty} x(t)\omega(t-\tau)e^{-j2\pi ft}dt \qquad (5)$$

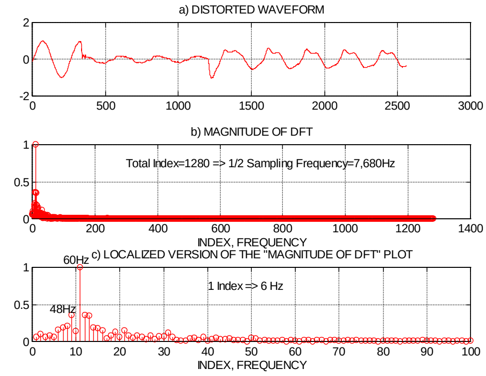

Fig. 5 (a) Actual voltage sag, (b) Its DFT, (c) Localized DFT.

The Windowed Discrete Fourier Transform (WDFT) is used for digital implementation of the STFT. It is defined as;

$$WDFT[k,m] = \sum_{n} x[n]\omega[n-m]e^{-\frac{j2\pi kn}{N}} \qquad (6)$$

where the sequence ω[n-m], in its simplest form, is a rectangular window function. Windowed DFT of Fig. 5 (a) is shown in Fig. 6. Here, a better spectrum of various frequency components are easily detectable. However, there still exists a drawback for WDFT, the frequency index becomes rougher. It was 6 Hz in DFT, but now is 60 Hz for WDFT.

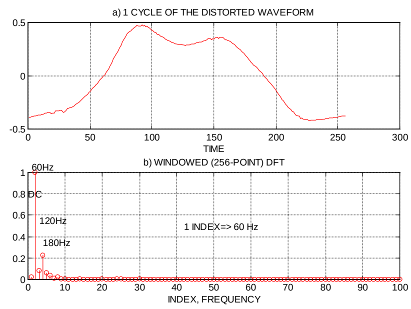

Fig. 6 (a) Windowed part of Fig. 5 (a), b) Its WDFT.

One should be very careful when utilizing the Windowed Fourier transform, especially the FFT (Fast Fourier Transform). Some of the important criteria other than the periodicity of the waveform and the Nyquist sampling frequency criterion are as follows:

(i) In one cycle of the waveform, the number of samples should be integer,

(ii) Within a window, the total number of cycles should also be integer,

(iii) One cannot use it when the waveform is nonstationary.

If these criteria are not met, then the resulting spectra obtained out of Fourier application has no meaning.

2.4 Missing Voltage Technique: To avoid mis-representing the waveform, another approach is introduced, called the missing voltage technique. The missing voltage is defined as the difference between the desired instantaneous voltage and the actual instantaneous value. The desired voltage is easily obtained by taking the pre-event voltage and extrapolating this out during the event, similar to the way a phase-locked loop (PLL) operates. A PLL is basically a control loop incorporating a voltage-controlled oscillator and phase sensitive detector in order to lock a given signal to a stable reference frequency. Therefore, we will call the desired voltage waveform the "PLL waveform" $v_{PLL}(t)$ and it will be locked in magnitude, frequency, and phase angle to the pre-event voltage waveform. The disturbed waveform is called $v_{sag}(t)$ and the missing voltage m(t) at any instant of time is the difference:

$$m(t) = v_{PLL}(t) - v_{sag}(t) \quad (7)$$

where m(t) gives the instantaneous deviation from the known reference.

As long as the voltage sag has a sinusoidal waveshape, the missing voltage will always be sinusoidal because of the properties of the trigonometric functions; the sum or the difference of two sinusoids results in another sinusoid with possible different phase. Therefore, the missing voltage has a certain phase relationship with respect to the phase of the pre-fault voltage.

Mathematically, let

$$\begin{aligned} v_{PLL}(t) &= A\sin(\omega t - \phi_a) \\ v_{sag}(t) &= B\sin(\omega t - \phi_b) \end{aligned} \quad (8)$$

where A, B are the amplitudes and ϕ_a , ϕ_b are the phase angles of the PLL and the sag voltages respectively. Assuming the same frequency for both, then m(t) can be expressed as;

$$m(t) = R\sin(\omega t - \psi) \quad (9)$$

where

$$R = \sqrt{A^2 + B^2 - 2AB\cos(\phi_b - \phi_a)} \quad (10)$$

and

$$\tan\psi = \frac{A\sin(\phi_a) - B\sin(\phi_b)}{A\cos(\phi_a) - B\cos(\phi_b)} \quad (11)$$

The missing voltage of the example in Fig. 2 is shown in Fig. 7. As expected, the missing voltage is of 6 cycles duration and has a peak amplitude deviation of 0.5 pu. By using the modeling equation (8) and then substituting A=1, B=0.5, ϕ_a=0, and ϕ_b=0 into (10) and (11), the resulting waveform of the form (9) will be m(t)=0.5sin(ωt) (with ψ =0). Note, however, that the actual missing voltage (83%) is much larger than the normalized RMS value as shown in Fig. 7 (b). By using the modeling eqn. (9) and then substituting A=1, B=0.5, ϕ_a=0, and ϕ_b= -56^0 into eqn. (10) and eqn. (11), the result in eqn. (9) will be m(t)=0.83 sin(ωt+30^0). The resulting phase difference between the PLL and the m(t) is about 30^0.

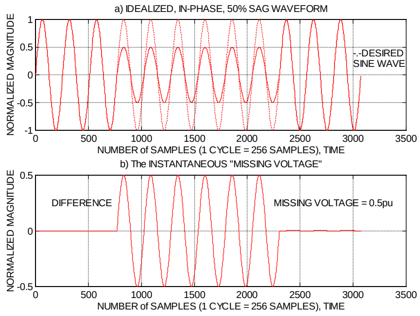

Fig. 7 (a) Sag waveform and desired sine-wave, (b) Missing voltage. Plots are normalized to peak =1.0 pu.

From the moving-window RMS computation, the event appears to last 7 cycles if both transitions are taken into account (normally the duration is defined as the time during which the RMS value ≤0.95 pu). In order to correct this phase voltage to the desired magnitude and phase relationship with the other phases, it is necessary to inject 0.83 pu peak voltage for about 6 cycles as depicted in Fig. 8 (b). The main reason for this discrepancy with the RMS is due to the phase shift during the fault.

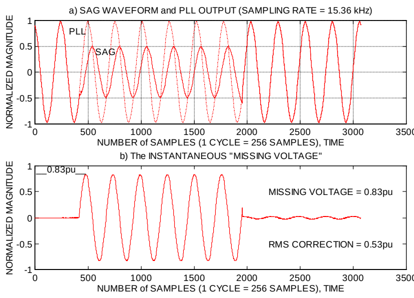

Fig. 8 (a) Sag waveform and desired sine-wave, (b) Missing voltage.

2.5 Wavelet Analysis Technique: The wavelet transform has received considerable interest in fields such as image processing, speech compression, acoustics, and seismics. Like the familiar Fourier Transform, the wavelet transform decomposes a signal into its frequency components. But, unlike the Fourier Transform, the wavelet transform provides a non-uniform division of the frequency domain. The decomposition is performed using a multi-resolution signal decomposition technique.

The wavelet transform can be related to the more commonly used Fourier transform or Fourier series. The Fourier models represent functions as weighted sum of exponentials at different frequencies. The weight at each different frequency is the Fourier coefficients. Wavelet models analogously represent functions as a weighted sum of scaled and translated mother wavelets. The wavelet transform has a mother wavelet that replaces the exponential; scaling and translation replace frequency shifting. The Wavelet Transform (WT) of a continuous signal x(t) is defined by

$$WT(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t) g\left[\frac{(t-b)}{a}\right] dt \qquad (12)$$

The signal x(t) is transformed by an analyzing function g(t). Here "a" is the scale parameter, and "b" is the translation parameter. A wavelet coefficient, WT(a, b), at a particular scale and translation, represents how well the signal, x, is similar to the scaled and translated mother wavelet. The wavelet g[(t-b)/a] is expanded or contracted in time depending on whether a>1 or a<1. As "a", scale parameter, is ranged over some interval, usually beginning with unity and increasing, the input is analyzed by an increasingly dilated function (lower frequencies) that is becoming less and less focused in time. Therefore, instead of continuous dilation and translation, the mother wavelet may be dilated and translated by selecting a and b as $a = a_0^m$ and $b = na_0^m$, where a_0 is a fixed constant and m, n ε Z , and Z is the set of positive integers. Then, the Discrete Wavelet Transform (DWT) is defined as

$$DWT[m,k] = \frac{1}{\sqrt{a_0^{\ m}}} \sum_n x[n] g\left[\frac{(k - na_0^{\ m})}{a_0^{\ m}}\right] \qquad (13)$$

where g[n] is the mother wavelet. Wavelet transform is very powerful tool for capturing the initiation and the recovery of voltage sags and appears sensitive to phase shifts and point-on-wave. However, one may not characterize the whole features of voltage sags by utilizing the wavelet analysis alone [9-14].

DWT of the sag waveform in Fig. 7 (a) can be seen in Fig. 9. Levels on the vertical scale indicates the particular scale parameter a_0^m, with a_0 being equal to 2.

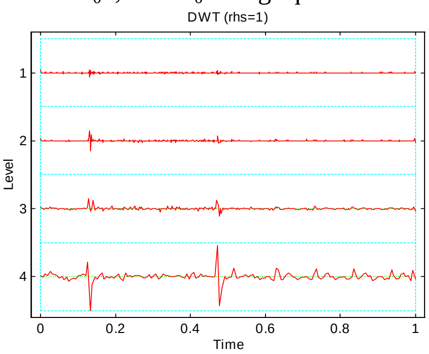

Fig. 9 DWT of the sag waveform in Fig. 7 (a).

The highest frequency components are seen at LEVEL 1. At every increase in LEVEL, the original signal is high-passed with the wavelet filter Daubechies' Orthogonal Least Asymmetric (DOLA2) filter and the total number of sampled data is reduced by half by downsampling. The transient energy is filtered through successive stages until only the underlying fundamental at 60 Hz and its sub frequencies are left. At level 1, some impulse like short duration, less energy carrying 7,680 Hz components exist. It is clear that DWT captures the beginning and the end of the sag at 2^{nd} level. Level 1 corresponds to 7,680 Hz, level 2 to 3,840 Hz, level 3 to 1,920 Hz, and level 4 to 960 Hz. Amplitude of the transforms gets larger when the levels increase especially during the initiation and the termination of the sag.

III. CONCLUSIONS

Basic analysis tools for power transient waveforms are introduced. Problems and limitations associated with the RMS and Fourier transform techniques are discussed. A new analysis tool is proposed, namely "Missing Voltage Technique", and a brief detail is given. Newly emerging techniques of Wavelet transform techniques are also briefly introduced. Main advantages and limitations for each technique are evaluated.

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