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# Discrete Wavelet Analysis Based Processing of Short-Duration Voltage Variations

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***Abstract— The aim of this paper is to obtain information about sinusoidal voltage signals, in which variations occur for a short duration, using wavelet analysis based signal processing methods. Sag, swell and interruption are short-duration voltage variations. The changes that occur in supply voltage are to be analyzed properly to initiate correct preventive measures. Multiresolution analysis based discrete wavelet transform is used for decomposing the original signals into five levels of approximations and details. Energy for wavelet decomposition and entropy are used for feature extraction and an attempt is made to obtain an information from the disturbance signals. Pure sinusoidal signal is used as reference and all the voltage variations are generated using SIMULINK in MATLAB environment. Energy values of one approximation and of details corresponding to all levels one to five are obtained. Shannon, log energy and norm entropy values are obtained for five level approximations and details. The term level refers to decomposition level. An observation is made between the obtained energy and entropy values of all the signals and for each variation, energy and entropy values are distinguishable for different disturbances.***

***Index Terms—Approximations, details, discrete wavelet transform, energy, entropy.***

## I. INTRODUCTION

Distribution of electric power has to be carried out by electric utilities without any interruption. The loads connected will be affected due to the sudden changes in supply voltage. To prevent the impact of the variations in supply voltage across the connected load, it is necessary to analyze voltage signals. The term, 'power quality' is widely used in literature for implementation of the objective of power supply without any deviations. Power quality is defined as a set of boundaries that allows electrical systems to function in their intended manner without significant loss of performance [1]. Due to disturbances, the equipment connected across the supply will be damagingly affected due to changes in any one of voltage, current or frequency.

Power quality disturbances are a result of the faults on transmission lines which include any of the line to ground, line to line, double line to ground faults or three phase faults with or without ground involvement. Due to any of these faults, there will be a deviation in the pure sinusoidal supply voltage. The aim of this paper is to obtain an information about the voltage variation signals by processing the signals using discrete wavelet analysis based signal processing method. The paper is organized with an explanation about the short-duration voltage variations in section 2, and generation of voltage signals using MATLAB/ SIMULINK in section 3. Discrete wavelet transform based decomposition of the signals into approximations and details is explained is explained in section 4. Section 5 includes processing of signals by energy and entropy values obtained and last section ends with conclusion.

## II. SHORT-DURATION VOLTAGE VARIATIONS

IEEE standard 1159 -1995 [2], defined different power quality disturbances for monitoring electric power quality. Short-duration voltage variations fall under second category out of seven broadly classified power quality disturbances. Short-duration voltage variations are further classified as voltage sag, swell and interruption. Voltage sag is a decrease in voltage to between 0.1 per unit and 0.9 per unit for durations from 0.5 cycles to 1 minute [2]. Voltage swell is an increase in voltage above 1.1 per unit for durations from 0.5 cycle to 1 minute [2]. An interruption occurs when the supply voltage or load current decreases to less than 0.1 per unit for a period of time not exceeding 1 minute [2]. In all the definitions, the term voltage refers to root mean square value of voltage. Short-duration voltage variations are depicted in fig.1.It is observed that due to sag, swell and interruption there is a decrease in magnitude of voltage, increase in magnitude of voltage and complete loss of voltage respectively for a duration.

The waveforms in fig.1 can be obtained by writing mathematical equations as MATLAB code in MATLAB command window or in an m-file. The equations depend on various parameters like magnitude at the time of disturbance and duration of the disturbance. The same waveforms in fig.1 can also be obtained by using different SIMULINK models in MATLAB. In this paper, the signals of sag, swell and interruption are generated using SIMULINK models in MATLAB. Three phase voltage waveforms are generated from which single phase waveforms are considered for analysis.

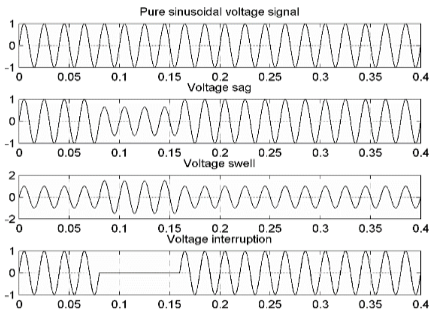


**Fig.1: Single phase voltage signal signals with voltage magnitude on y-axis and time on x-axis (a) \Sinusoidal voltage signal (b) Sag (c) Swell (d) Interruption**

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## III. GENERATION OF VOLTAGE SIGNALS USING MATLAB/ SIMULINK AND RESULTS

In all the three SIMULINK models shown in figures 2, 3 and 4, a synchronous generator of nominal power 4200MVA with mechanical power as input is used with three wire star connection. Line to line voltage is 13.8kV and number of pole pairs are two. Series RLC load is connected across the generator with an active power of 200MW and zero inductive reactive power and zero capacitive reactive power. A distributed line is used of length 100 km. Resistance and inductances of the two windings are 0.002 and 0.08 respectively measured in per unit. A line to ground fault is initiated between one phase and ground with fault resistance of 0.0005Ω and ground resistance of 0.001Ω. Load comprises of resistance 3Ω and inductance of 50mH connected in series.

### *A. Sag*

Simulink model for voltage sag generation is shown in fig.2. A three winding linear transformer with a nominal power of 250MVA is used. For the transformer, primary winding voltage is 13.8kV and secondary winding voltage is 600V.

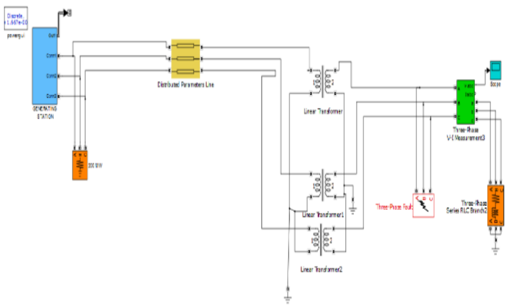

**Fig.2: Simulink model for generation of voltage sag**

### *B. Swell*

In the Simulink model for swell generation shown in fig.3, RL and RLC branches are connected. For RL branch resistance is 72.6Ω and inductance is 0.173H. For RLC branch, resistance is 1Ω, inductance is 1mH and capacitance is 1 μF. The three terminals from generator are connected to RL load through a circuit breaker with a phase to phase voltage of 3kV.

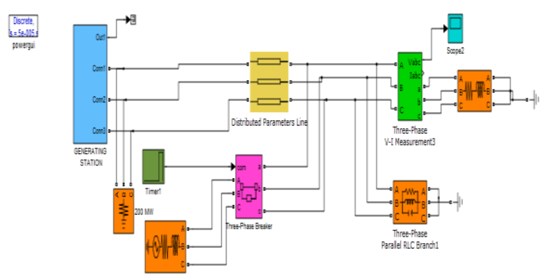

**Fig.3: Simulink model for generation of voltage swell**

### *C. Interruption*

In the Simulink model for an interruption generation shown in fig.4, a fault is initiated between all the three phases and ground with fault resistance of 0.001Ω and ground resistance of 0.001Ω. The distributed line is terminated by a three phase RLC load with nominal phase to phase voltage of 1000V. Active power of load is 10kW and the same inductive and capacitive reactive power of 100VAR.

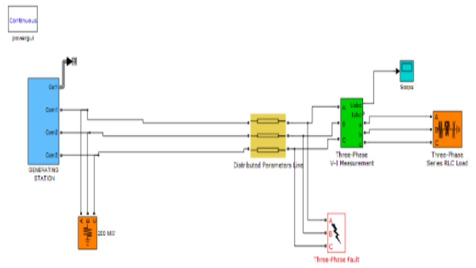

**Fig.4: Simulink model for generation of an interruption**

The scope connected in figures 2, 3 and 4 respectively depict reduction in voltage, increase in voltage and loss of voltage for a certain duration. Voltage waveforms at the load side are observed in scope block connected through three phase voltage measurement block in all the three Simulink models. By using single phase voltage measurement block along with scope, single phase voltage waveforms will be displayed.

## IV. WAVELET DECOMPOSITION

Due to the changes that occur in supply voltage, there will be deviation in sinusoidal voltage resulting in disturbances in the voltage supplied. Discrete wavelet transform is used for signal processing of voltage signals. By applying discrete wavelet transform, any signal can be decomposed into approximations and details. Any function in time domain is represented by discrete wavelet transform as [3],

$$f(t) = \sum_k c_j(k) 2^{j/2} \ \varphi(2^j t - k) + \sum_k d_j(k) 2^{j/2} \ \psi(2^j t - k) \quad (1)$$

The first summation in (1) gives a function that is of low resolution termed as approximation of the signal. The second summation gives a higher or finer resolution termed as detail.

The term *j* j refers to scaling parameter and *k* k refers to shift parameter. Approximations and details are obtained through a succession of convolution process [3].Approximation and detail coefficient vectors are represented as cA and cD with the level of decomposition as subscript. The coefficient vectors can be generated for all the considered levels of decomposition. Wavelet analysis is the breaking up of a signal into shifted and scaled versions of the original (or mother) wavelet [4]. Daubechies 4 (db4) wavelet is used as mother wavelet. For illustration, an interruption signal is considered to depict discrete wavelet analysis and decomposition is carried out resulting in generation of approximation coefficient vectors ( $cA_1$, $cA_2$, $cA_3$, $cA_4$ and $cA_5$) and detail coefficient vectors ($cD_1$, $cD_2$, $cD_3$, $cD_4$ and $cD_5$).


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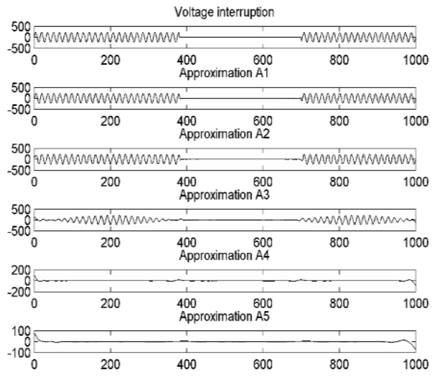


**Fig.5: Levels 1 to 5 approximations of voltage interruption signal obtained by wavelet decomposition**

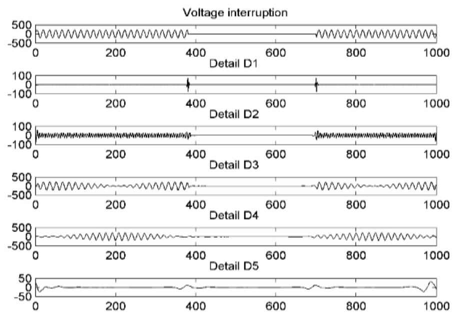


**Fig.6: Levels 1 to 5 details of voltage interruption signal obtained by wavelet decomposition**

**Table 1 Lengths of approximation and detail coefficient vectors**

| Level | Signal | Rows | Columns |
|---|---|---|---|
| 1 | $cA_1$ and $cD_1$ | 6545 and 6545 | 1 and 1 |
| 2 | $cA_2$ and $cD_2$ | 3276 and 3276 | 1 and 1 |
| 3 | $cA_3$ and $cD_3$ | 1641 and 1641 | 1 and 1 |
| 4 | $cA_4$ and $cD_4$ | 824 and 824 | 1 and 1 |
| 5 | $cA_5$ and $cD_5$ | 415 and 415 | 1 and 1 |

The dimensions for approximation and detail coefficient vectors of all the considered SIMULINK generated signals which are of same length are given in table 1. From the obtained coefficient vectors, approximations and details are constructed by extraction of approximation and detail coefficients. Approximations ($A_1$, $A_2$, $A_3$, $A_4$ and $A_5$) and details ($D_1$, $D_2$, $D_3$, $D_4$ and $D_5$) are obtained from coefficient vectors. Approximations ($A_1$, $A_2$, $A_3$, $A_4$ and $A_5$) are shown in fig.5 and details ($D_1$, $D_2$, $D_3$, $D_4$ and $D_5$) are shown in fig.6 along with original signal.

## V. DISCRETE WAVELET ANALYSIS BASED SIGNAL PROCESSING

In order to obtain useful information from the signals, processing of the signals is to be performed. Energy and entropy are the two features used for extraction of an information from the signals. The approximations are the high-scale, low-frequency components of the signal and the details are low-scale, high-frequency components [4]. In [5], multiresolution signal decomposition technique is used for decomposing a signal into its detailed and smoothed versions where detailed version consists of sharp edges, transitions and jumps. Discrete wavelet transform is a time-scale analysis method that is particularly suitable for detecting transition or singular points in the signal waveforms and decomposes a signal into multi-resolution components [6]. It is reviewed in [7] that wavelet theory acts as a powerful tool in power quality area for the analysis of power quality disturbance signals.

### *A. Energy*

The term energy is referred as energy for 1-D (one dimensional) wavelet decomposition. In MATLAB, Energy values are obtained for all the five levels of details and one approximation using db4 mother wavelet. Table 2 shows the energy values for wavelet using db4 mother wavelet.

**Table 2 Energy values for wavelet decomposition**

| | Energy values | | | |
|---|---|---|---|---|
| Signal | Sine | Sag | Swell | Interruption |
| A5 | 99.996 | 99.936 | 99.982 | 99.8654 |
| D1 | 0 | 0.0022 | 0.0004 | 0.0067 |
| D2 | 0 | 0.0008 | 0.0014 | 0.0021 |
| D3 | 0.0001 | 0.0074 | 0.0051 | 0.0212 |
| D4 | 0.0006, | 0.0059 | 0.0028 | 0.0095 |
| D5 | 0.0030 | 0.0477 | 0.0077 | 0.0951 |

All the short-duration voltage variation signals represent a disturbance or variations on comparison with a pure sine signal. So the difference in energy values corresponding one approximation and five level details for both the signals are different as shown in table 2. . Signal processing is carried out using energy values to obtain an information about the variation resulted with respect to pure sinusoidal voltage.

### *B. Entropy*

Entropy is used for feature extraction and out of the entropy types of Shannon entropy, log energy entropy, norm entropy, threshold entropy and SURE entropy, the considered types for analysis are Shannon entropy, log energy and norm entropy. In [8], voltage signals are generated based on mathematical equations and an attempt is made to classify short-duration voltage variations, using wavelet decomposition based entropy criteria. The signals of pure sine, sag, swell and interruption are taken into consideration for five level decomposition. Entropy values of signals before decomposition, termed as original signals, are shown in table 3. The approximation and detail coefficient vectors of the voltage signals for five levels are returned to real numbers which represent entropy values and are tabulated in tables 4 to 7. Shannon entropy is non-normalized entropy involving the logarithm of the squared value of each signal sample given as, $-\sum s_i^2 \log(s_i^2)$ [4]. Log energy entropy is the logarithm of "energy" entropy, defined as the sum over all


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samples given as, $\sum \log(s_i^2)$ [4]. Log energy entropy curves obtained for extracted approximation and detail coefficient vectors from level 1 to 5 decomposition are shown in fig.10. Norm entropy is defined as concentration in $l^p$ norm with $1 \leq p$ with the parameter $p$ taken as 1.5 [4].

**Table 3 Entropy Values Of Original Signals (Before Decomposition)**

| Signal | Log energy | Shannon | Norm |
|---|---|---|---|
| Sine | 3.84e4 | -4.65e12 | 5.33e9 |
| Sag | 3.76e4 | -4.02e12 | 4.78e9 |
| Swell | 4.41e4 | -1.90e13 | 1.42e10 |
| Interruption | 3.37e4 | -3.89e12 | 4.39e9 |

A clear distinguish in the entropy values can be observed from the Shannon, log energy and norm entropy values are obtained for both level 1 to 5 approximations and details returned as real numbers. Based on the real numbers obtained using MATLAB given in tables 4 to 7. Norm entropy values are always positive. The two discrete wavelet analysis based features energy and entropy give information about the signal after processing the signals.

**Table 4 Entropy values for approximations (A) and details (D) of sine signal for levels 1 to 5**

| A | Log energy | Shannon | Norm | D | Log energy | Shannon | Norm |
|---|---|---|---|---|---|---|---|
| 1 | -1.2566e4 | -1.2743e7 | 0.6353e6 | 1 | -25.2761 | -0.0408e9 | 0.0833e6 |
| 2 | -0.4937e4 | -5.7050e7 | 0.9984e6 | 2 | -214.6553 | -0.1001e9 | 0.2424e6 |
| 3 | -0.1821e4 | -1.8912e7 | 1.0246e6 | 3 | -25.0544 | -1.1499e9 | 1.2499e6 |
| 4 | -0.0602e4 | -0.1649e7 | 1.2354e6 | 4 | 16.5497 | -0.1012e9 | 0.2886e6 |
| 5 | -0.0153e4 | -8.0971e7 | 2.0552e6 | 5 | 3.0239 | -0.0555e9 | 0.1443e6 |

**Table 5 Entropy values for approximations (A) and details (D) of sag signal for levels 1 to 5**

| A | Log energy | Shannon | Norm | D | Log energy | Shannon | Norm |
|---|---|---|---|---|---|---|---|
| 1 | -1.2571e4 | -0.7398e6 | 0.8492e5 | 1 | -31.2648 | -0.1836e7 | 0.0936e5 |
| 2 | -0.4944e4 | -2.2413e6 | 1.3283e5 | 2 | -222.6647 | -0.5695e7 | 0.3254e5 |
| 3 | -0.1822e4 | -1.0312e6 | 1.3558e5 | 3 | -30.4464 | -6.6263e7 | 1.6598e5 |
| 4 | -0.0605e4 | -0.0884e6 | 1.6334e5 | 4 | 8.4705 | -0.5601e7 | 0.3807e5 |
| 5 | -0.0159e4 | -4.5220e6 | 2.7151e5 | 5 | -2.3829 | -0.3065e7 | 0.1904e5 |

**Table 6 Entropy values for approximations (A) and details (D) of swell signal for levels 1 to 5**

| A | Log energy | Shannon | Norm | D | Log energy | Shannon | Norm |
|---|---|---|---|---|---|---|---|
| 1 | -1.2556e4 | -0.2937e10 | 1.4779e6 | 1 | -33.3987 | -0.0008e9 | 0.1852e6 |
| 2 | -0.4931e4 | -0.5188e10 | 2.3223e6 | 2 | -218.9282 | -0.2268e9 | 0.5661e6 |
| 3 | -0.1778e4 | -0.4595e10 | 2.3806e6 | 3 | 1.1350 | -2.0273e9 | 2.9094e6 |
| 4 | -0.0567e4 | -0.7887e10 | 2.8707e6 | 4 | 26.9320 | -0.3260e9 | 0.6703e6 |
| 5 | -0.0139e4 | -1.5106e10 | 4.7756e6 | 5 | 35.3376 | -0.0858e9 | 0.3352e6 |

**Table 7 Entropy values for approximations (A) and details (D) of an interruption signal for levels 1 to 5**

| A | Log energy | Shannon | Norm | D | Log energy | Shannon | Norm |
|---|---|---|---|---|---|---|---|
| 1 | -1.2566e4 | -1.1559e7 | 0.5940e6 | 1 | -25.4440 | -0.0372e9 | 0.0781e6 |
| 2 | -0.4937e4 | -5.1829e7 | 0.9335e6 | 2 | -214.9260 | -0.0909e9 | 0.2266e6 |
| 3 | -0.1821e4 | -1.7185e7 | 0.9581e6 | 3 | -25.2336 | -1.0460e9 | 1.1685e6 |
| 4 | -0.0602e4 | -0.1497e7 | 1.1552e6 | 4 | 16.2806 | -0.0920e9 | 0.2699e6 |
| 5 | -0.0153e4 | -7.3613e7 | 1.9218e6 | 5 | 2.8449 | -0.0505e9 | 0.1349e6 |

## VI. CONCLUSION

Three phase short-duration voltage waveforms are generated using MATLAB/ SIMULINK. Single phase voltage signals of sine, sag, swell and interruption are considered for analysis. By using discrete wavelet transform, the signals are decomposed into approximations and details for five levels. Two discrete wavelet analysis based features, energy and entropy are used for processing of the signals. Energy values are obtained for fifth level approximation and one to five level details. Shannon entropy, log energy entropy and norm entropy are used to obtain real numbers as entropy values. Based on the obtained energy and entropy values, the disturbances are distinguishable. A comparison can be made by observing a deviation of energy and entropy values of sag, swell and interruption with respect to the values of that of a pure sinusoidal signal.

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