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Algorithms for Detecting Missing Voltage and Motor Starting Events

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Algorithms for Detecting Missing Voltage and Motor Starting Events

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This work is dedicated to my parents and sister.

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Algorithms for Detecting Missing Voltage and Motor Starting Events

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The objective of this work is to develop algorithms to detect voltage variation events in power quality data and to figure out their characteristics. Voltage variation events covered in this work are missing voltage and motor starting events. The first part of this work describes the fundamental concept, characteristics and sources of voltage variation events. Next, this work describes the algorithms to detect voltage variation events. The verification of the algorithms is performed using simulated data from PSCAD/EMTDC and actual field data. The results show that the performance of the algorithms and the characteristics of voltage variation events are satisfactory. This work contributes to the development of detecting voltage variation events from a real distribution system and the analysis of voltage variation events.

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Chapter 1

Introduction

1.1 Motivation and Objective

Power quality refers to the maintenance of voltage, current, and frequency to certain limits [1]. In particular, the demand for preventing short-duration voltage variations in power quality is rapidly increasing. Among these short duration variations, voltage variation events may cause disturbances in a power system by electrical devices. Voltage sag happens by various sources, thus the detection of voltage sags and the determination of their sources is a significant issue to improve power quality. By detecting voltage sags and determining their sources, it is possible to estimate and avoid disturbances in a power system.

The goal of this work is to develop algorithms to detect and analyze voltage variation events. The performance of algorithms is also evaluated. The work will first provide the structure of algorithms based on the characteristics of voltage variation events. Then, the algorithms will be verified using simulation data. Finally, actual data from a power system will be applied to algorithms so that the performance can be validated.

1.2 Approach and Results

The first approach of this work is to describe the fundamental concept of voltage variation events. Thus, some background on voltage variation events is summarized in Chapter 2. The definition and characteristics of voltage variation events provided in Chapter 2 will be used to develop algorithms to detect and analyze specific events. Next, the structure of algorithms to detect and analyze voltage variation events will be provided in Chapter 3. The data format used for the algorithms will be described as well. Chapter 3 will also describe theories and formulas used in the algorithms. The description of the algorithms will be provided by dividing two sections according to the type of events. Chapter 4 will evaluate the developed algorithms with simulation data from PSCAD/EMTDC. Chapter 4 will describe simulation models and simulation conditions of voltage variation events. The simulation will involve missing voltage events and motor starting events. Simulation data collected from PSCAD/EMTDC will be applied to the algorithms in Chapter 4. The accuracy of the algorithms will be verified by comparing results to conditions of simulation. Based on the results of simulation data in Chapter 4, the application to real utility data will be presented in Chapter 5. The real utility data will be applied to the algorithms for missing voltage events and motor starting events separately. Algorithms will detect and analyze missing voltage events and motor starting events, respectively. The results show the detected events and their characteristics.

1.3 Contribution

The primary contribution of this work is the development of detecting, determining, and analyzing voltage variation events: missing voltage events and motor starting events. Developed algorithms detect not only voltage sags, but also the event type of voltage variation based on the characteristics of events. Additionally, results from algorithms show the characteristics of events like duration, magnitude and inrush current. The validation of algorithms by simulation data provides confidence of performance of algorithms to detect and analyze voltage variation events. It is meaningful that the verified algorithms by simulation data can detect and determine voltage variation events from the actual data of a real power system. Based on results, detected voltage variation events will be analyzed so that the causes of them will be estimated. The estimation can help in predicting and preventing voltage variation events in the future.

Chapter 2

Overview of Voltage Variations

Chapter 2 covers the background on voltage variation among categories of power quality phenomena. As presented in Chapter 1, power quality disturbances are significant problems in power distribution systems. The Institute of Electrical and Electronics Engineers (IEEE) classifies power quality phenomena into seven categories based on their typical spectral content, duration and voltage magnitude [2]. This classification is shown in Table 2.1. The algorithms of this work will detect short-duration variation events. Missing voltage events and motor starting events, which will be detected, determined and analyzed, pertain to interruption and voltage sags of short duration variation. Thus, the algorithms will be developed to detect interruption and sag in voltage. For this development, this chapter will describe the fundamental concept of interruption and voltage sags in order to understand the characteristics of interruption and voltage sags. Additionally, the explanation of missing voltage events and motor starting events will be provided with features of these events.

Table 2.1: Categories and typical characteristics of power system electromagnetic phenomena [2]

No.	Categories	Typical spectral content	Typical duration	Typical voltage magnitude
1.0	Transient			
1.1	Impulsive			
1.1.1	Nanosecond	5 ns rise	< 50 ns	
1.1.2	Microsecond	1 μs rise	50 ns-1 ms	
1.1.3	Millisecond	0.1 ms rise	> 1 ms	
1.2	Oscillatory			
1.2.1	Low frequency	< 5 kHz	0.3-50 ms	0-4 pu
1.2.2	Medium frequency	5-500 kHz	20 μs	0-8 pu
1.2.3	High frequency	0.5-5 MHz	5 μs	0-4 pu
2.0	Short duration variations			
2.1	Instantaneous			
2.1.1	Sag		0.5-30 cycles	0.1-0.9 pu
2.1.2	Swell		0.5-30 cycles	1.1-1.8 pu
2.2	Momentary			
2.2.1	Interruption		0.5 cycles-3 s	< 0.1 pu
2.2.2	Sag		30 cycles-3 s	0.1-0.9 pu
2.2.3	Swell		30 cycles-3 s	1.1-1.4 pu
2.3	Temporary			
2.3.1	Interruption		3 s-1 min	
2.3.2	Sag		3 s-1 min	0.1-0.9 pu
2.3.3	Swell		3 s-1 min	1.1-1.2 pu
3.0	Long duration variations			
3.1	Interruption, sustained		> 1 min	0.0 pu
3.2	Undervoltages		> 1 min	0.8-0.9 pu
3.3	Overvoltages		> 1 min	1.1-1.2 pu
4.0	Voltage imbalance		steady state	0.5-2 %
5.0	Waveform distortion			

Table 2.1 (continued)

5.1	DC offset		steady state	0-0.1 %
5.2	Harmonics	0-100th H	steady state	0-20 %
5.3	Interharmonics	0-6 kHz	steady state	0-2 %
5.4	Notching		steady state	
5.5	Noise	broad-band	steady state	0-1 %
6.0	Voltage fluctuations	< 25 Hz	intermittent	0.1-7 %
7.0	Power frequency variations		< 10 s	

2.1 Short-Duration Variations

Voltage in a power system is not always the same as the nominal value of voltage. When the voltage has abnormal value, the situation is called variation. Variation needs to be evaluated since it usually occurs in a power system [7].

Short-duration variations are disturbances which last for 0.5 cycles to 1 minute. The magnitude of short-duration variations has magnitudes of 0 to 1.2 pu. As shown in Table 2.1, short-duration variations are categorized as instantaneous (between 0.5 and 30 cycles), momentary (between 30 and 3 seconds) and temporary (between 3 seconds and 1 minute) by duration, and as interruption (less than 0.1 pu), sag (between 0.1 and 0.9 pu) and swell (between 1.1 and 1.4 pu) by the magnitude of voltage.

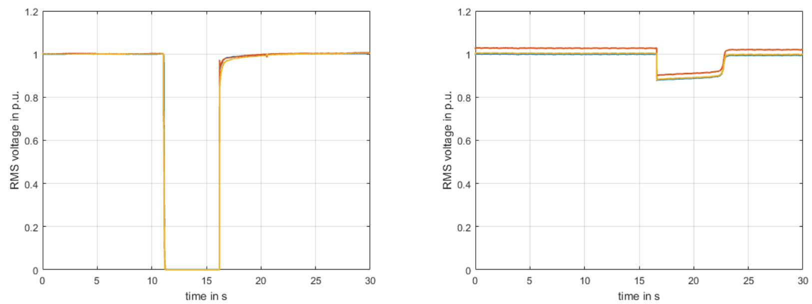
Short-duration variations are usually caused by fault conditions and the subsequent operation of devices to protect from overcurrent. Depending on the fault and the system conditions, an interruption, voltage sag or swell can occur. The following section will introduce the interruption and voltage sag phenomena related to missing voltage events and motor starting events.

2.1.1 Interruption

An interruption is a disturbance in which its voltage falls to about 0. IEEE regards a disturbance in which RMS voltage is less than 10% of nominal voltage as an interruption. The duration of interruptions by a fault can be determined by the operating time of protective devices, while the duration of interruption by malfunctions can be irregular. Interruptions by a fault follow voltage sags [10, 12, 16, 20, 21].

2.1.2 Voltage Sags

A voltage sag is a phenomenon where RMS voltage decreases. IEEE defines cases in which supplying voltage has between 0.1 and 0.9 pu as voltage sag. The two terms are considered interchangeable, although the term sag is the preferred term in the U.S. power quality. Voltage sag usually occurs due to faults on a power system, energization of heavy loads or starting of large motors. When an induction motor starts, its load current generally goes up to 6 to 10 times. The current due to the starting of the induction motor is so inductive that it causes a voltage sag. A voltage sag is one of the most concerning issues, since it is the most common power quality disturbance. Thus, it needs to be detected and analyzed for its features and sources [3, 4, 12, 13, 17, 18, 20].



(a) Interruption (b) Voltage sag

Figure 2.1: Interruption and voltage sag in RMS voltage

2.1.3 Characteristics of Interruption and Voltage Sags

There are some characteristics of interruption and voltage sags, such as magnitudes, duration, missing voltage, phase angle shifts and so on. This chapter covers, in detail, the magnitude, duration and missing voltage which will be used in algorithms.

2.1.3.1 Magnitudes

Power quality disturbances are categorized by the typical voltage magnitude as shown in Table 2.1. This means that the magnitude of power quality disturbances is a very essential feature. The magnitude of a voltage sag is usually measured in root mean square (RMS) value at the power frequency (50 or 60 Hz). For calculating the RMS value of continuous signals, frequency components should be considered. Thus, only the fundamental frequency component must be used to compute the RMS value. However, waveform data from actual power system is a discrete signal. Thus, the computation of the RMS value for discrete signal needs the number of samples in one period. This note will be considered in Chapter 3. There can be a confusion of the terminology describing the magnitude of a voltage sag because both the depth of a voltage sag and the minimum value during a voltage sag are used to represent the magnitude of a voltage sag. However, the lowest RMS value during a voltage sag is used in general. Thus, in this work, the algorithms will use the minimum RMS value as the magnitude of a voltage sag. Additionally, the magnitude of a voltage sag is measured in the per unit value [12, 20].

2.1.3.2 Duration

The duration is also a meaningful feature of a voltage sag since the performance of electronic devices is affected by duration. Computing the duration of a voltage sag is complicated. The duration is determined by the difference between the starting point, where the RMS voltage value falls below 0.9 pu, and the end point, where the RMS voltage value recovers over 0.9 pu [12, 20].

We will use different computations for following missing voltage events and motor starting events in the algorithms. For missing voltage events, we will compute the duration of events in a waveform. To obtain the significant value of the duration, we determine the starting point of events corresponding to the voltage of waveform converging to 0 and the end point of events corresponding to the voltage of waveform recovering its original signal from 0. The duration is the difference between the start and end points.

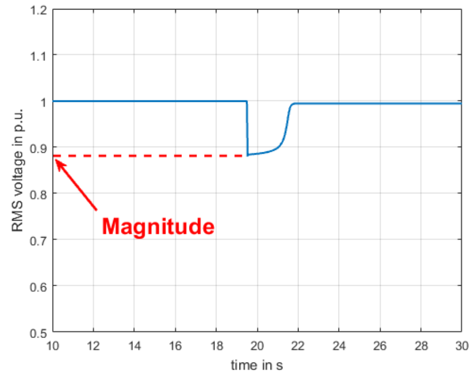
However, for motor starting events, the duration of events will be computed in RMS value. The starting point of events is defined as the point at which RMS voltage falls down and the end point as the point at which RMS voltage recovers its nominal value. If voltage does not recover, the end point is regarded as the point at which RMS voltage saturates. These computations of duration will be thoroughly provided in Chapter 3.

2.1.3.3 Missing Voltage

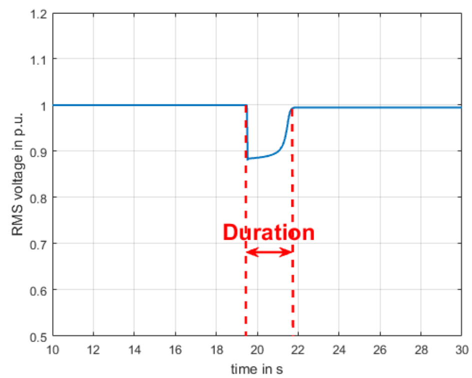
Missing voltage is computed as the instantaneous difference between the desired voltage and the actual measured voltage during voltage sag. The missing voltage ΔV follows equation 2.1.

$$\Delta V[n] = V_s[n] - V_m[n] \tag{2.1}$$

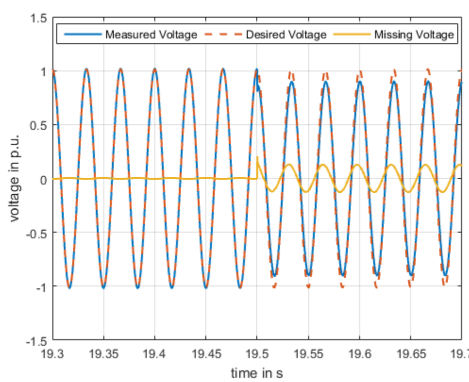
where V_s is the synthesized voltage and V_m is the actual measured voltage. The missing voltage is a useful characteristic to negate and compensate for voltage sags [11, 22]. Thus, it is very important to detect missing voltage and figure out causes of missing voltage for supplying stable voltage.



(a) Magnitude



(b) Duration



(c) Missing voltage

Figure 2.2: Illustration of magnitude, duration and missing voltage

2.2 Missing Voltage Events

Missing voltage events can be defined as events which have missing voltages described in the previous section. However, only events in which measured voltage goes to 0 are considered as missing voltage events in this work. That is, the conditions of missing voltage events are as follows in equation 2.1.

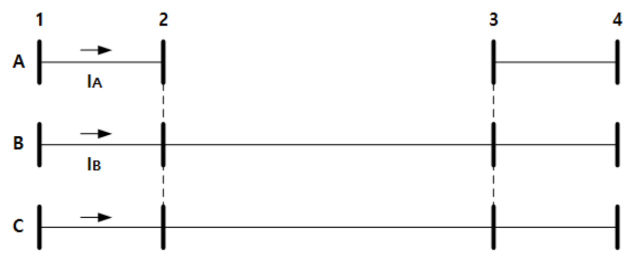
1. $\Delta V \simeq V_s$

2. $V_m \simeq 0$

One of the causes of events in which the measured voltages go to 0 is an open conductor fault. Open conductor faults can occur by opening the transmission lines shown as Figure 2.3. Physically broken transmission lines due to accidents or storms can cause open conductor faults [23].

At the downstream (bus 3 shown in Figure 2.3) of the location where open conductor faults occur, voltages are measured zero. When all of the three phases are open as in Figure 2.3a, V_a, V_b and V_c of bus 3 are zero, and I_a, I_b and I_c are also zero. When only one phase of three phases is open, like Figure 2.3b, the circuit is unbalanced and asymmetrical currents flow. This circuit is described as $I_a = 0$, $V_{b,\,2-3} = 0$ and $V_{c,\,2-3} = 0$. Similarly, if any two of three phases are open, the circuit becomes unbalanced and asymmetrical currents flow. In this case, it shows that $I_b = 0$, $I_c = 0$ and $V_{a,\,2-3} = 0$. Open conductor faults can be analyzed using the bus impedance matrices of the sequence networks.

(a) Three phases are open



(b) One phase is open

(c) Two phases are open

Figure 2.3: Open conductor events

2.3 Motor Starting Events

When motors start to operate, inrush current, which is 5 to 6 times of normal current, flows through circuits until motors are in steady state. A magnetic field is created when motors start. By Maxwells equations, a magnetic field in motors leads to an induced current. Since the magnetic field is large and the winding of motors typically has very low resistance, the induced inrush current would be large. This inrush current causes a voltage sag. The characteristics of voltage sag when motor starts depend on the characteristics of motors such as the size of motors, the method of motor starting and load size, as well as the tolerance of circuit system connected to motors. The magnitude of a voltage sag can be largely effected by the impedance of circuits. The single-line diagram of motor starting events can be simply drawn as Figure 2.4.

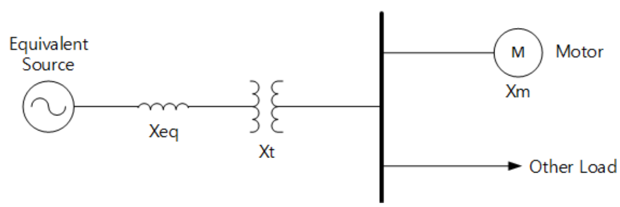


Figure 2.4: Single-line diagram of motor starting events

Shown in Figure 2.4, we can describe the lowest voltage and the line current through the motor when a motor starting event occurs as follows,

$$\begin{aligned} V_{sag} &= \frac{X_m}{X_{eq} + X_t + X_m} V_s \\ I_{line} &= \frac{V_s}{X_{eq} + X_t + X_m} \end{aligned} \tag{2.2}$$

In above equation, V_s is the source voltage, and X_{eq}, X_t and X_m are the equivalent positive-sequence short-circuit reactance, the leakage impedance of the transformer and the equivalent reactance of the motor at the rated frequency, respectively.

The most significant characteristic of motor starting events is that they show a sharp drop and gentle return to the normal state in RMS voltage. This RMS voltage variation usually takes a few seconds. This is because the magnitude of the inrush current decreases gradually after the induction motor starts. This feature of voltage variation in motor starting events is quite distinct from voltage sag due to faults. Additionally, since induction motors are 3-phase balanced loads, 3-phase voltage waveforms have a similar shape with each other. Based on these characteristics of voltage and current in motor starting events, the next chapter will discuss the algorithm to detect motor starting events [5, 6, 8, 9, 15, 20].

Chapter 3

Improved Detection of Events

This chapter discusses data format as well as the entire detection algorithm. It first describes data format to help understand the way the algorithm is developed. Then, it explains the entire algorithm of detection stage by stage. The algorithm consists of a data processing part and a detection part. The data processing part resamples, corrects phase sequences, and transforms waveforms to RMS for detection. In the detection part, the algorithm detects missing voltage (or current) events and motor starting events using various criteria.

3.1 Data Format

The structure of data format is very simple. Each data include waveforms of 3-phase voltage (V_A, V_B and V_C) and current (I_A, I_B, I_C and I_N). Magnitudes of voltage and current are recorded in time. There are two types of data. One has 500,000 records of magnitude for 30 seconds, while the other has 250,000 records of magnitude for 30 seconds. Thus, data need to be sorted by two types in the data processing part. Furthermore, voltage of some data are not sequential voltage series, which means that phase B and phase C are changed with each other. Some data also have mismatched phases A, B and C between voltage and current respectively. These would be handled in data processing part as well.

3.2 Detection Algorithm

The algorithm is divided into two parts: data processing and detection. In the data processing part, the algorithm adjusts and modifies data for the detecting part. To detect characteristics of voltage sag due to missing voltage events and motor staring events simply, resampling, correction of phase, and root mean square (RMS) value are used in this part. Subsequently, the algorithm detects voltage sag first by using RMS value of voltage, and each feature of waveform can classify specific events from entire data.

3.2.1 Data Processing

The data processing procedure is described as follows. Data processing is the preparation stage to detect events. To detect events correctly, it needs to confirm that data has errors in phases of voltage (or current). For error correction, the algorithm uses fast Fourier transform. By using fast Fourier transform, the algorithm figures out each phase of waveform. The original sample of data should be coordinated to the integer sampling rate to calculate fast Fourier transform. Thus, resampling should be the first stage of data processing. After resampling, phases of waveforms in data need to be corrected as previously stated. In this process, fast Fourier transform is used. Followed by resampling and correction of phases, waveforms of data are transferred into RMS value for detecting voltage sag. Figure 3.1 describes the data processing stage.

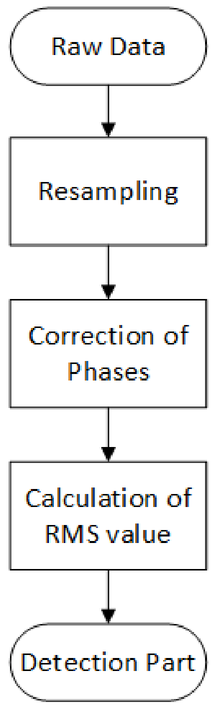


Figure 3.1: Flowchart of data processing

3.2.1.1 Resampling

The algorithm uses fast Fourier transform and root mean square value. To calculate fast Fourier transform and root mean square value properly, the sampling rate should be an integer. However, the original sampling rate of 500,000 data recorded for 30 seconds is 277.7778 samples per cycle. Since the frequency of the original data is 60 Hz, during 30 seconds, the data has 1,800 cycles in itself. The original sampling rate, 277.7778, is calculated by dividing 500,000 data samples by 1,800 cycles. To get an integer sampling rate, the new sampling rate should be set up as 256 samples per cycle. Depending on the new sampling rate, 256 samples per cycle, the number of data samples is changed from 500,000 to 460,800. For 250,000 data recorded during 30 seconds, the original sampling rate of data is 133.8889 samples per cycle. Similarly, to change an integer sampling rate, the new sampling rate for 250,000 data is 128 samples per cycle. Thus, in this case, the number of data samples is 230,400.

3.2.1.2 Correction of Phase

As mentioned above, phases of voltage in some data are not in the correct sequence. Though the difference between phase A and B, phase B and C, and phase C and A should be $\frac{2\pi}{3}$, that of phase A and C has $\frac{2\pi}{3}$ (theoretically, that value should have $-\frac{2\pi}{3}$). In addition, some data have mismatched phases A, B and C between voltage and current respectively. For example, the phase difference between V_B and V_C is $\frac{2\pi}{3}$, while the phase difference between I_B and I_C is $-\frac{2\pi}{3}$. It is assumed that the data recorded wrong or phases were labeled incorrectly. Thus, not only do correct phases need to be figured out, but phases of voltage also need to coincide with those of current. To correct these errors, phases of waveforms should be calculated using fast Fourier transform. After each value of phases of waveform is provided by fast Fourier transform, each waveform of V_A, V_B and V_C will have its proper phases A, B or C, through comparing the value of phases. The equation of fast Fourier transform is as follows [19].

$$X(e^{jw}) = \sum_{n=-\infty}^{\infty} x[n]e^{-jwn} \tag{3.1}$$

MATLAB provides the `fft` function to calculate phase of waveform. Since calculating phases at every time takes too long, phases of only the first 10 periods are calculated. It is assumed that there might be no event during the first 10 periods. That period can be set up to another number, such as 5, in this algorithm. Through the `fft` function, we can calculate phase of each waveform, θ_A, θ_B and θ_C. Comparing the values of phases θ_A, θ_B and θ_C, V_B and V_C are determined based on V_A. If the difference between θ_A and θ_B is $\frac{2\pi}{3}$, while that between θ_A and θ_C is $-\frac{2\pi}{3}$ respectively, the data of this case is correct. If not, V_B and V_C need to be swapped, since the data is wrongly recorded. After waveforms of voltage change to be correct, waveforms of current need to change similarly. To determine waveforms of current correctly, the algorithm compares power factor. Power factor is calculated from dividing active power by complex power. Complex power is the vector sum of active and reactive power. We can note it as follows [14].

$$S = VI^* = [V\underline{/\theta_V}][I\underline{/\theta_I}]^* = VI\underline{/\theta_V - \theta_I} \tag{3.2}$$

$$S = P + jQ \tag{3.3}$$

$$pf = \frac{P}{S} \tag{3.4}$$

Hence, the magnitude and phase of voltage and current are calculated from fast Fourier transform. As before, we assume that there is no event in the beginning part of the data. We first calculate N periods of fast Fourier transform for one period moving a quarter of a period. One period has 256 samples, thus a quarter of a period has 64 samples. For example, N could be 10. The next step is to calculate complex power S and active power P for each period. Active power P is the real part of complex power S. The final step is to calculate 10 values of power factor and the average of 10 values of power factor. When comparing the power factors, it is possible to find I_A, I_B and I_C corresponding to V_A, V_B and V_C respectively.

3.2.1.3 Root Mean Square Value

After phase correcting, the algorithm calculates root mean square value from waveforms. This is because voltage sag is detected in RMS value first. Root mean square value can be calculated as follows [20].

$$V_{rms} = \sqrt{\frac{1}{N}\sum_{n} v^2[n]} \tag{3.5}$$

We calculate RMS value for one period (256 samples), moving the start point a quarter of a period (64 samples). Since the moving window size is 64 samples, 7,200 RMS values are created for 460,800 sample points. 7,200 is derived from dividing 460,800 by 64. In the same way, 230,400 samples transfer to 3,600 RMS values. In addition, the last 3 RMS values cannot be determined because the width window size N is 256. Thus, to derive 7,200 (or 3,600) numbers of RMS value, we set the first 4 RMS values equal to the first RMS value.

3.2.2 Detection of Missing Voltage Events

First of all, to detect missing voltage events, we need to detect voltage sag from the RMS figure. Voltage sag is defined in the previous chapter. The algorithm takes the magnitude of voltage sag as an input variable. Thus, only voltage sag, which has magnitude within the input variable range, is detected. If voltage sag is detected, the algorithm figures out the start point index $T_{start,rms}$ as well as the end point index $T_{end,rms}$ of voltage sag in RMS figures.

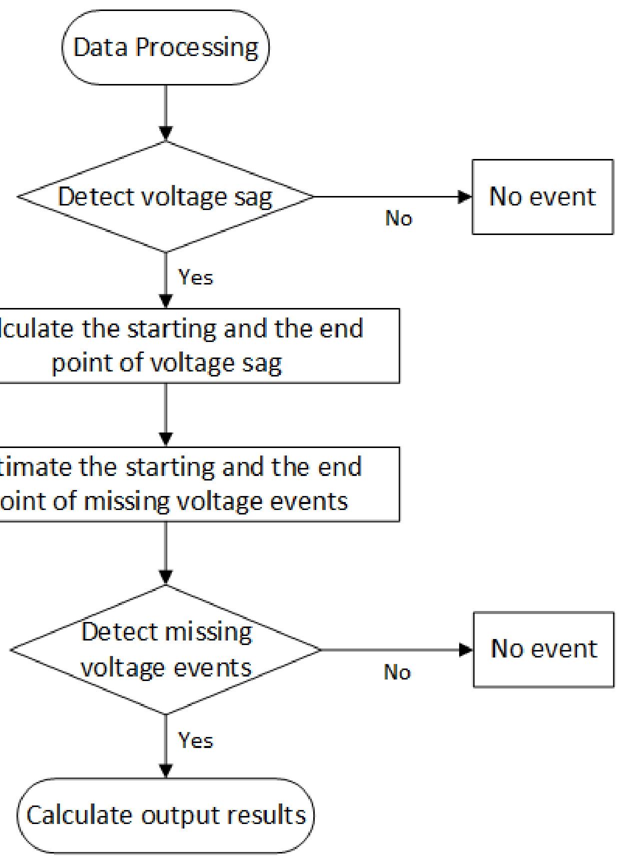


Figure 3.2: Flowchart of detection for missing voltage events

Afterwards, the algorithm detects missing voltage (and current) in the detected event of RMS figure. The algorithm checks if there is missing voltage (and current) event between $T_{start,\,rms}$ and $T_{end,\,rms}$ in waveform figure according to characteristics of missing voltage event mentioned in the previous chapter.

Before detecting missing voltage (and current) in waveform, we need to find the proper index of $T_{start,\,rms}$ and $T_{end,\,rms}$ for an original waveform, since $T_{start,\,rms}$ and $T_{end,\,rms}$ are determined from the RMS figure. Note that the total number of values in the original form is 500,000 (or 250,000) while the total number of values in RMS is 7,200 (or 3,600). Thus, to figure out $T_{start,\,original\,waveform}$ and $T_{end,\,original\,waveform}$, we need to consider resampling and calculating RMS. The number of samples in the resampled waveform reduces when RMS values are calculated for 256 samples by moving 64 samples of the window. In reverse, $T_{start,\,resampled\,waveform}$ and $T_{end,\,resampled\,waveform}$ are estimated by following equations.

$$\begin{aligned} W(T_{start,\,rms} - 3 - 1) + 1 \leq T_{start,\,resampled\,waveform} \\ \leq W(T_{start,\,rms} - 3 + 3) \end{aligned} \tag{3.6}$$

$$\begin{aligned} W(T_{end,\,rms} - 3 - 1) + 1 \leq T_{end,\,resampled\,waveform} \\ \leq W(T_{end,\,rms} - 3 + 3) \end{aligned} \tag{3.7}$$

In this case, W is 64. -3 should be inserted in the above equation since we set the first 4 RMS values equal to the first RMS value.

Additionally, because there are losses of samples due to resampling, we also need to consider this loss to estimate more exact points of event. The ratio of resampling is $\frac{2304}{2500}$. Thus, the start and end index of events in original waveform apply the equation below.

$$T_{start,\,original\,waveform} = T_{start,\,resampled\,waveform} \times \frac{2500}{2304} \tag{3.8}$$

$$T_{end,\,original\,waveform} = T_{end,\,resampled\,waveform} \times \frac{2500}{2304} \tag{3.9}$$

Then, substituting equation (3.8) and (3.9) to equation (3.6) and (3.7), we obtain,

$$\begin{aligned} \{W(T_{start,\,rms} - 3 - 1) + 1\} \times \frac{2500}{2304} &\leq T_{start,\,original\,waveform} \\ &\leq \{W(T_{start,\,rms} - 3 + 3)\} \times \frac{2500}{2304} \end{aligned} \tag{3.10}$$

$$\begin{aligned} \{W(T_{end,\,rms} - 3 - 1) + 1\} \times \frac{2500}{2304} &\leq T_{end,\,original\,waveform} \\ &\leq \{W(T_{end,\,rms} - 3 + 3)\} \times \frac{2500}{2304} \end{aligned} \tag{3.11}$$

According to equation (3.10) and (3.11), we can figure out an estimation of the start and end point. However, the estimation values are not exact points of event. Thus, we need to find missing voltage only within the estimation range of the starting point, $\{W(T_{start,\,rms} - 3 - 1) + 1\} \times \frac{2500}{2304}$, and the end point, $\{W(T_{end,\,rms} - 3 + 3)\} \times \frac{2500}{2304}$.

The conditions for detecting missing voltage (and current) events are as follows.

C.1 Is there missing voltage in waveform?

C.2 Is there current voltage in waveform?

The condition of missing voltage is defined as the part in which values are continuously 0. The algorithm only detects events satisfying the condition within that range. As a result, algorithm figures out the exact starting point, $T_{start,\, original\, waveform}$, and the end point, $T_{end,\, original\, waveform}$ of event in the original waveform. Figure 3.3 and 3.4 describe this flow. Figure 3.3 and 3.4 are graphs of V_A as an example of missing voltage event. Figure 3.3 shows RMS of V_A with the presence of a voltage sag. Voltage sag occurs between the start index, $T_{start,\, rms}$, and the end index, $T_{end,\, rms}$. They are 2668 and 3890, respectively. Accordingly, the estimation of the starting point and the end point of the missing voltage event could be $\{W(T_{start,\, rms}-3-1)+1\} \times \frac{2500}{2304} \approx$ 185001 and $\{W(T_{end,\, rms}-3+3)\} \times \frac{2500}{2304} \approx 270139$. These points are shown on figure 3.4. The precise range of missing voltage is 185525 to 269898 within the estimated range.

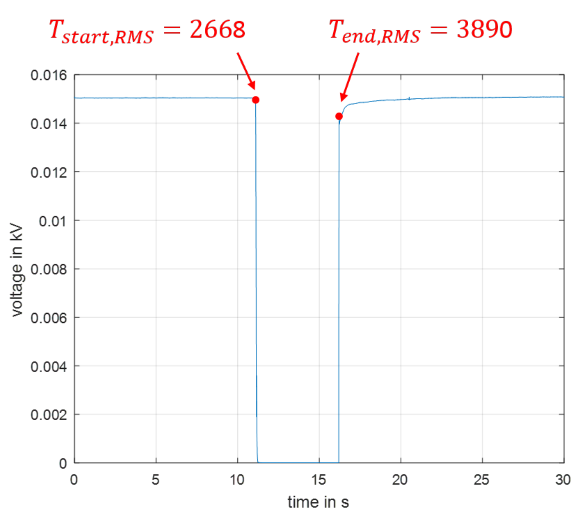


Figure 3.3: An example RMS of V_A of missing voltage event

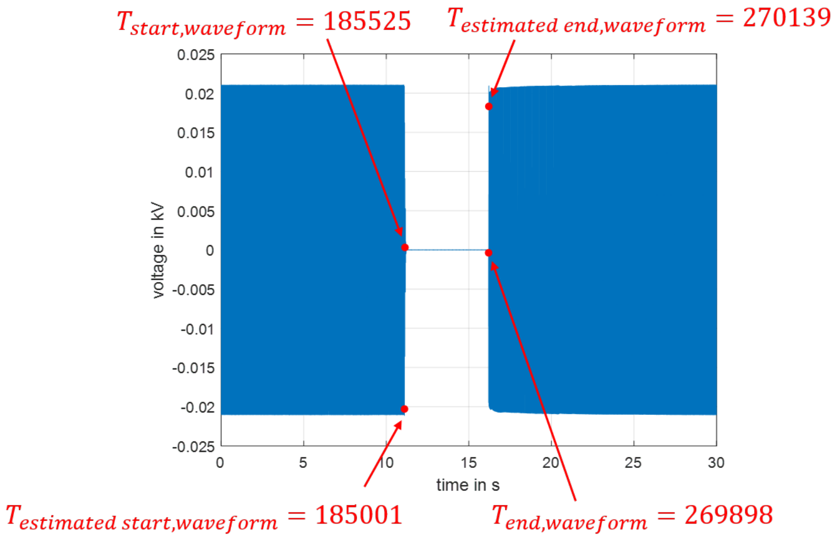


Figure 3.4: An example waveform of V_A of missing voltage event

Based on these exact points, $T_{start,\,original waveform}$ and $T_{end,\,original waveform}$, algorithm returns duration of missing voltage event.

$$\text{Duration} = (T_{end,\,original\;waveform} - T_{start,\,original\;waveform}) \times \frac{\text{Total Time}}{\text{Number of Samples}} \tag{3.12}$$

Finally, the algorithm returns the mean of voltage during the exact points to double-check for missing voltage events.

Detecting missing current events is the same as detecting missing voltage events. Based on the estimated range in voltage waveform, the algorithm figures out the exact range of missing current events, and returns the duration and the mean of current for that range.

Note the difference in the number of samples by sampling and calculation of RMS.

3.2.3 Detection of Motor Starting Events

Just as missing voltage events are computed, detection for motor starting events begins with detecting voltage sag in RMS figures. The algorithm takes the magnitude of voltage sag as an input variable for detecting only the voltage sag, which has a magnitude within the input variable range as well.

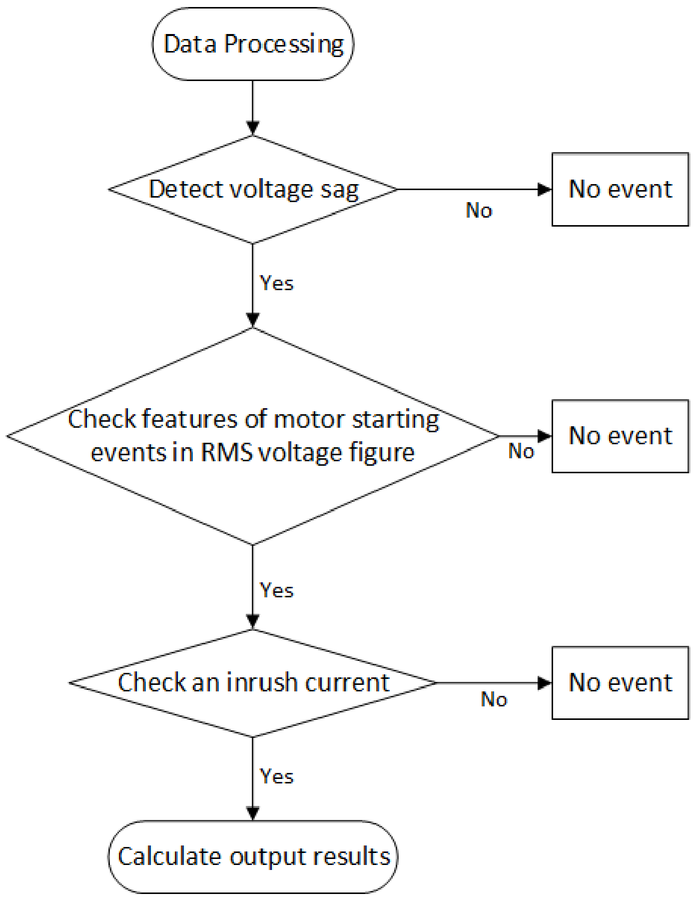


Figure 3.5: Flowchart of detection for motor starting events

If a voltage sag is detected in the RMS figure, the algorithm analyzes the figure of RMS voltage and current, while the algorithm for detection of missing voltage events computes with waveforms.

The conditions for detecting motor starting event are as follows.

C.1 RMS Wave Shape for Voltage

C.2 Inrush Current

C.1 is applied to RMS voltage. As stated in the previous chapter, events by motor starting have the specific characteristics in the shape of the graph of RMS voltage: 1) RMS voltage drops sharply 2) RMS value of voltage continues steadily for a short time 3) RMS voltage recovers gently. These are described in Figure 3.6. Thus, the algorithm checks if the detected event, in which voltage sag occurs, has such shape of figure for RMS voltage.

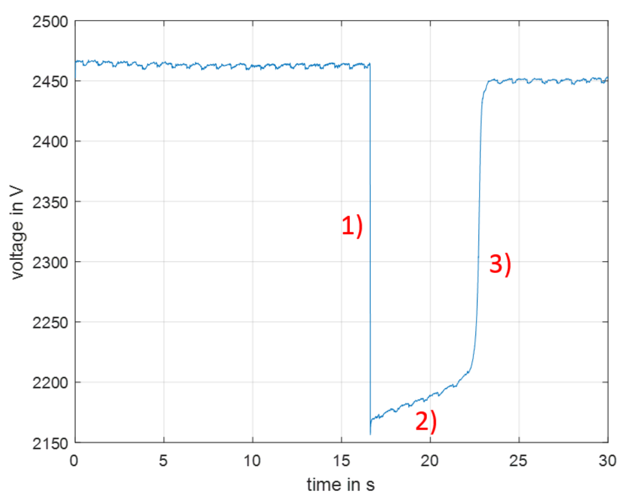


Figure 3.6: An example RMS of V_A of motor starting event

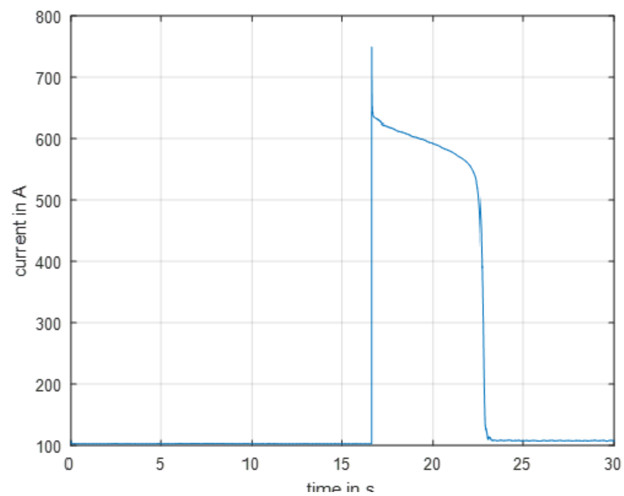


Figure 3.7: An example RMS of I_A of motor starting event

In case of a motor starting event, current increases rapidly when voltage sag occurs. We call this an inrush current. Thus, based on RMS current, the algorithm detects motor starting event if there is an inrush current as Figure 3.7.

After motor starting event is detected, the algorithm returns the duration of event in RMS, the lowest value in RMS during motor starting event, the difference between voltage of start point and end point, and the peak inrush current.

Chapter 4

Implementation of Detection in Power System Simulation

To evaluate algorithms to detect events of missing voltage and motor starting, it is important to develop a simulation model for various conditions. Simulation provides diverse situations and more accurate data by operating conditions, so that we can evaluate algorithms before applying them to utility data. Simulation evaluates not only specific cases in a real power system, but also exceptional cases which are not normal in a real power system. We can model various distribution circuits in PSCAD/EMTDC software. In this section, we discuss the implementation of a PSCAD/EMTDC simulation model for events of missing voltage and motor starting. The objective of simulation is to examine the algorithms to detect events accurately. Thus, we need to model a fundamental distribution system in software according to missing voltage events and motor starting events first. The next process will add scenarios to develop various situations possible to occur in real distribution system. We can get data for each phase of voltage and current based on a distribution circuit model and scenarios from simulation. Applying this data to algorithms, we will check that algorithms provide expected results, and compare output from algorithms to simulation scenarios, so that we can verify algorithms. The first part explains PSCAD/EMTDC simulation. The next part shows simulation of missing voltage event, data from simulations, and results by algorithms, so that we can evaluate performance of algorithms. The last part performs the same process regarding motor starting events. As in the previous part, we proceed with simulation of motor starting events, obtain data from simulation, and analyze that data using algorithms.

4.1 PSCAD/EMTDC

PSCAD/EMTDC is a simulation software for analyzing power system. PSCAD/EMTDC consists of PSCAD, a program providing graphic user interface (GUI) and EMTDC, a simulation engine [24].

Models of synchronous generators, induction generators, power electronic elements, control system, motors and etc., are available in PSCAD/EMTDC.

On the basis of these functions, PSCAD/EMTDC software is often used to model distribution circuits. We will a develop fundamental distribution circuit model by this program, and perform simulations corresponding to missing voltage events and motor starting events. From simulations, we can obtain data of voltage and current. Note that we set the properties of data to have same number of samples to the number of samples in utility data. It is because the objective of simulation is to test algorithms before applying them to utility data. We check whether algorithms detect events accurately and output from algorithms is identical to the modeled situation. Lastly, we will discuss results.

4.2 Simulation of Missing Voltage Events

This section explains simulation of missing voltage events. It will be examined that the algorithms properly detect events in data from simulation, and perform exact calculation by comparing the output from algorithms with the situation provided by the simulation.

4.2.1 Distribution Circuit Model for Missing Voltage Event

Figure 4.1 describes one-line diagram of the distribution circuit for missing voltage events, and Figure 4.2 is a PSCAD/EMTDC model according to Figure 4.1. Figure 4.1 represents a fundamental distribution circuit. This circuit consists of an equivalent source, transformers, a load and a switch. Note that a switch is located for reproducing missing voltage events.

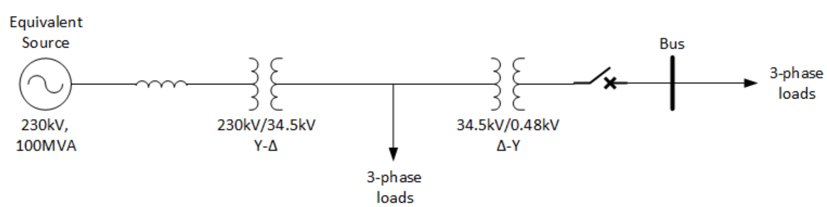


Figure 4.1: One-line diagram of distribution circuit model for missing voltage events

The equivalent source operates at 230 kV. Its positive and zero sequence impedances are $(0.135 + j0.835) \times 10^{-2}$ p.u. and $(0.105 + j0.640) \times 10^{-2}$ p.u. on 100 MVA base. The transmission line is set to 100 miles long with the

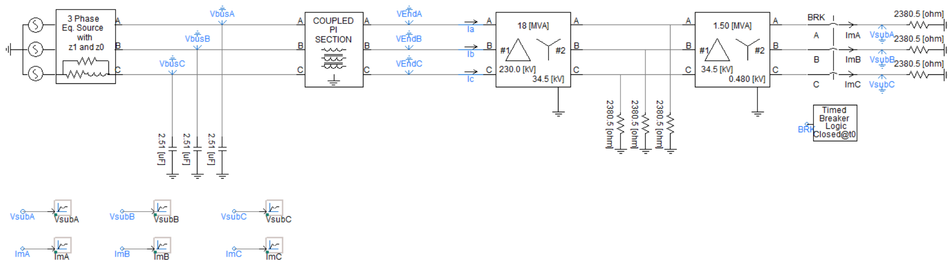


Figure 4.2: PSCAD distribution circuit model for missing voltage events

following positive and zero sequence impedances, $z_1 = 1.72 + j14.33$ p.u./m and $z_0 = 11.9 + j42.53$ p.u./m. Transformer 1 is Y-$\triangle$ transformer which winding is 230 kV/34.5 kV rated at 18 MVA, while transformer 2 is $\triangle$-Y transformer which winding is 34.5 kV/0.48 kV rated at 15 MVA. Appropriate loads are attached. Note that a timed breaker is used as a function of switch. To realize missing voltage events, we will open the distribution circuit and close it again during simulation. The easiest way to control distribution circuit open and close in PSCAD program is to use breakers. We can control breakers to be opened and closed at any time while the simulation runs. Thus, we locate breakers at each phase on the distribution circuit. For testing various general cases of missing voltage events, we make and simulate 6 cases depending on the status of breakers.

We make 6 cases because of the start time and duration of missing voltage events. Cases represent that the start time of missing voltage events is random and the duration of missing voltage events is very short (less than 10 cycles), short (less than 100 cycles) or long (about 500 cycles).

Voltage and current of 3 phases are measured on $VsubA$, $VsubB$ and

Table 4.1: Cases of simulation for missing voltage events

Case	Initial Status of Breaker	Open Time	Close Time
1	close	3.0	3.15
2	close	3.0	4.65
3	close	3.0	11.35
4	close	6.3	6.45
5	close	6.3	7.95
6	close	6.3	14.65

$VsubC$ bus on distribution circuit shown Figure 4.2. Lastly, it needs to set conditions of simulation in"Project Settings". As stated above, we set the number of estimated output data. Duration of simulation and the number of samples should be decided in this part. Utility data consists of 250,000 or 500,000 values for 30 seconds, respectively, as we mention in Chapter 3.1. For reducing the size of data, we need to generate data to have 250,000 values for 15 seconds similar to the utility data. Data which have 500,000 values for 30 seconds are skipped since they are too long. We need to set up "Duration of run", "Solution time step" and "Channel plot step" in "Project Settings". "Duration of run" is the duration time of simulation, and set up to 15 seconds. "Solution time step" is the period to calculate data of simulation, and "Channel plot step" means the period to plot data of simulation. Thus, "Solution time step" should be less than or equal to "Channel plot step". "Channel plot step" is 60 μs calculated by $\frac{15\,\text{sec}}{250000}$, and "Solution time step" is set up to be the same as "Channel plot step". An example of simulation from such settings is shown in Figure 4.9.

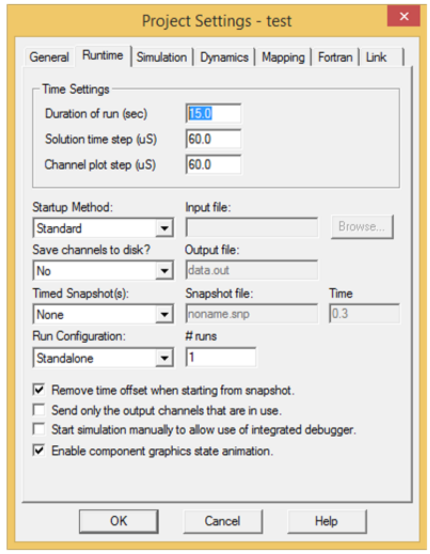
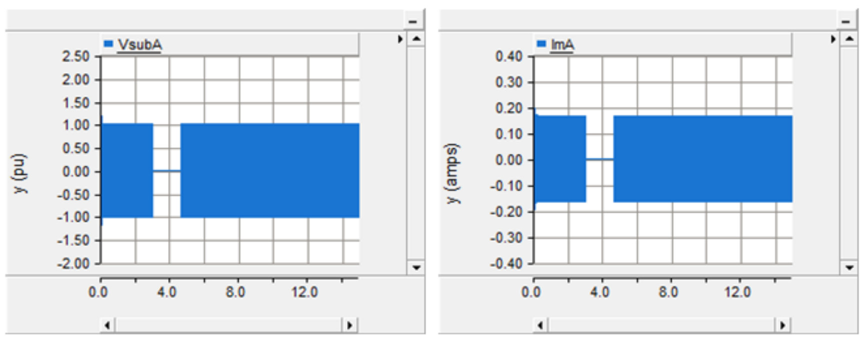


Figure 4.3: Project setting of PSCAD/EMTDC simulation



(a) Voltage of phase A (b) Current of phase A

Figure 4.4: An example of PSCAD/EMTDC simulation for missing voltage events

4.2.2 Results from Simulation of Missing Voltage Events

First of all, we need to evaluate correction of phase in the data processing part. As shown in the following table, the differences between each phase have nearly 2.0944 ($= \frac{2}{3}\pi$) radian in all cases. Figure 4.5 also shows phases sequential.

Table 4.2: Results of simulation for correction of phase

Case	Phase A to B (rad)	Phase B to C (rad)	Phase C to A (rad)
1	2.4748	2.1329	1.6755
2	2.4748	2.1329	1.6755
3	2.4748	2.1329	1.6755
4	2.4748	2.1329	1.6755
5	2.4748	2.1329	1.6755
6	2.4748	2.1329	1.6755

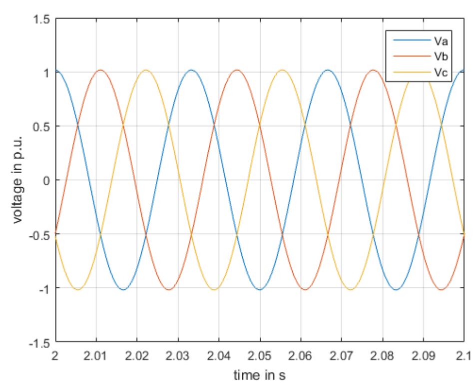


Figure 4.5: An example of phase sequence

According to the results of simulation, we can verify that our algorithms accurately detect 6 cases of missing voltage events. Algorithms detect missing voltage events as well as missing current events. Error of duration is given by equation 4.1.

$$\%\,\mathrm{Error} = \frac{\mathrm{T}_{\mathrm{detection}} - \mathrm{T}_{\mathrm{simulation}}}{\mathrm{T}_{\mathrm{simulation}}} \times 100 \tag{4.1}$$

To review errors of duration, all cases have less than 5% of error, so that durations are precisely calculated by algorithms. The reason for small errors is that breakers open at zero-crossing point of the current. We can check that the mean of voltage in output is 0 during the missing voltage event. As a result, the performance of algorithms is verified to detect missing voltage events. The following tables indicate the result of 6 cases, and Figure 4.6 shows the detected range in each voltage waveform of 6 cases.

Table 4.3: Results of simulation for missing voltage events (V_A)

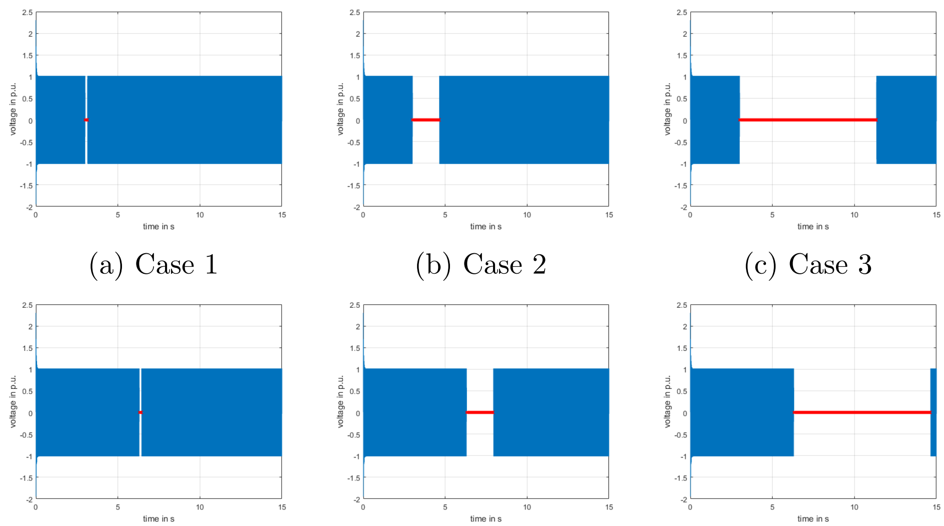
Case	Event Detected	Simulation Duration (ms)	Detected Duration (ms)	Error of Duration (%)	Mean of Voltage During Events (p.u.)
1	Yes	150	144.9006	3.3996	-0.5778×10^{-4}
2	Yes	1650	1644.9066	0.3087	-0.5100×10^{-5}
3	Yes	8350	8344.9534	0.0604	-0.1006×10^{-5}
4	Yes	150	144.9006	3.3996	$-0.5778 \times 10-4$
5	Yes	1650	1644.9066	0.3087	$-0.5099 \times 10-5$
6	Yes	8350	8344.9534	0.0604	$-0.1003 \times 10-5$

Table 4.4: Results of simulation for missing voltage events (V_B)

Case	Event Detected	Simulation Duration (ms)	Detected Duration (ms)	Error of Duration (%)	Mean of Voltage During Events (p.u.)
1	Yes	150	148.4406	1.0396	-0.0562×10^{-4}
2	Yes	1650	1648.4466	0.0941	0.0058×10^{-5}
3	Yes	8350	8348.4934	0.0180	-0.0230×10^{-5}
4	Yes	150	148.4406	1.0396	0.0582×10^{-4}
5	Yes	1650	1648.4466	0.0941	0.0236×10^{-5}
6	Yes	8350	8348.4934	0.0180	-0.0113×10^{-5}

Table 4.5: Results of simulation for missing voltage events (V_C)

Case	Event Detected	Simulation Duration (ms)	Detected Duration (ms)	Error of Duration (%)	Mean of Voltage During Events (p.u.)
1	Yes	150	142.8606	4.7596	0.8452×10^{-4}
2	Yes	1650	1642.8666	0.4323	0.7768×10^{-5}
3	Yes	8350	8342.9134	0.0849	0.1751×10^{-4}
4	Yes	150	142.8606	4.7596	0.8439×10^{-4}
5	Yes	1650	1642.8666	0.4323	0.7624×10^{-5}
6	Yes	8350	8342.9134	0.0849	0.1642×10^{-5}



(a) Case 1 (b) Case 2 (c) Case 3

(d) Case 4 (e) Case 5 (f) Case 6

Figure 4.6: Voltage of missing voltage events

4.3 Simulation of Motor Starting Events

As we run simulation of missing voltage events in the previous chapter, we will implement simulation of motor starting events in this section. We apply algorithms to data from simulation, and algorithms analyze simulation data regarding motor starting events. Algorithms decide if simulation data have motor starting events or not. When algorithms detect motor starting events from simulation data, they calculate the magnitude of voltage sag, the difference between voltage before events and after events, the duration of motor starting events, and the peak of inrush current. Based on output result by algorithms, we verify that algorithms reasonably perform the detection of motor starting events.

4.3.1 Distribution Circuit Model for Motor Starting Event

The one-line diagram of the equivalent distribution circuit for motor starting events is shown on Figure 4.7. It is the fundamental distribution circuit composed of the equivalent source, transformers, loads, a breaker, and an induction motor. The breaker operates as a switch in this distribution circuit, the same as the distribution circuit model for missing voltage events. Figure 4.8 describes PSCAD/EMTDC model of Figure 4.7. The parameters of the equivalent source, the transmission line, the transformers, and the loads are equal to those of the distribution circuit model for missing voltage events. The positive and zero sequence impedances for the equivalent source are $(0.135 + j0.835) \times 10^{-2}$ p.u. and $(0.105 + j0.640) \times 10^{-2}$ on 100 MVA base. The equivalent source operates at 230kV. The transmission line is 100 miles with the positive and zero sequence impedances, $z_1 = 1.72 + j14.33$ p.u./m and $z_0 = 11.9 + j42.53$ p.u./m, respectively. The rating of Y-$\triangle$ transformer is 230 kV/34.5 kV rated at 18 MVA, and that of $\triangle$-Y transformer is 34.5 kV/0.48 kV rated at 15 MVA. The difference is that the 480V-500HP induction motor is connected to the distribution circuit instead of the load for motor starting events. Motor starting events occur when the breaker is closed to make the induction motor start.

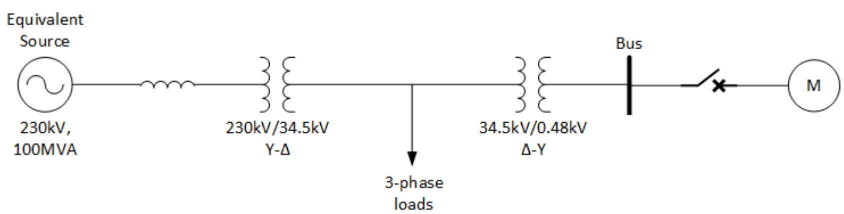


Figure 4.7: One-line diagram of distribution circuit model for motor starting events

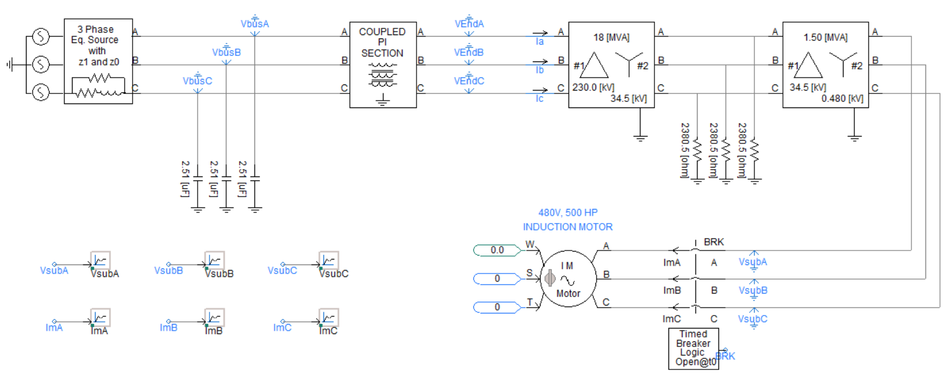


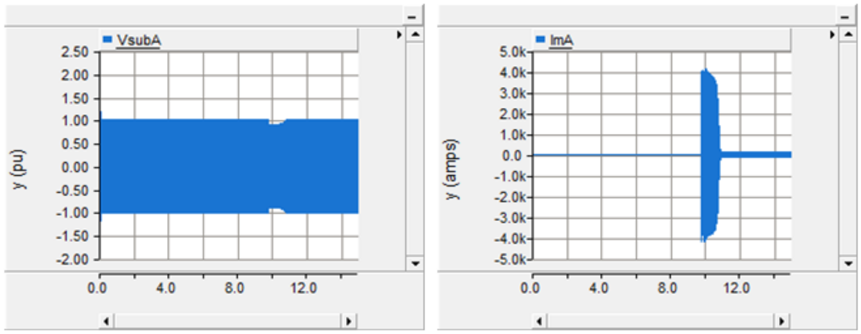
Figure 4.8: PSCAD distribution circuit model for motor starting events

We divide simulation into 6 cases as the angular speed of the induction motor and the closing time of the breaker for modeling various motor starting events. It is possible to simulate diverse motor starting events in which duration is different because the duration of motor starting events varies with the angular speed of the induction motor. The angular speed of the induction motor varies with the number of poles in the induction motor. Thus, the angular speed of the induction motor would be 125.66 rad/s, 188.50 rad/s, and 376.99 rad/s according to the number of poles, 2, 4 and 6, respectively. We can additionally apply different starting times of motor starting events to the algorithms. As simulation of missing voltage events, duration of run, solution

Table 4.6: Cases of simulation for motor starting events

Case	the angular speed (rad/s)	Initial Status of Breaker	Close Time
1	125.66	open	4.30
2	188.50	open	4.30
3	376.99	open	4.30
4	125.66	open	9.75
5	188.50	open	9.75
6	376.99	open	9.75

time step and channel plot step are configured as 15 seconds, 60 us and 60 us to create 250,000 numbers of data. Voltage and current are measured on the bus before the breaker.



(a) Voltage of phase A (b) Current of phase A

Figure 4.9: An example of PSCAD/EMTDC simulation for motor starting events

4.3.2 Results from Simulation of Motor Starting Events

The same as missing voltage events, the correction of phase is evaluated in motor starting events.

Table 4.7: Results of simulation for correction of phase

Case	Phase A to B (rad)	Phase B to C (rad)	Phase C to A (rad)
1	2.4749	2.1330	1.6753
2	2.4749	2.1330	1.6753
3	2.4749	2.1330	1.6753
4	2.4749	2.1330	1.6753
5	2.4749	2.1330	1.6753
6	2.4749	2.1330	1.6753

Algorithms detect all motor starting events from 6 cases of simulation. Explaining the columns of the result tables, voltage sag is the lowest value of RMS voltage during motor starting events. Voltage drop means the difference between RMS voltage before motor starting events and RMS voltage after motor starting events. Duration is the duration time of motor starting events. Inrush current means the peak value of RMS current during motor starting events.

To detect motor starting events, the variable of voltage sag range in algorithms is set from 0.6 to 0.95 p.u. As a result, we can check that the algorithms exactly detect motor starting events by the characteristic of voltage sag in motor starting events because all values of voltage sag in motor starting events are within the setting range. For inrush current, the algorithms are set to detect motor starting events only if the inrush current is more than 2 times above the base current. Consequently, we can see that the peak value of the inrush current is more than 2 times above the base current.

Table 4.8, 4.9 and 4.10 show that voltage sag and duration decrease as the angular speed of induction motor increases. Duration is exactly in inverse proportion to the angular speed of induction motor. Inrush current, on the contrary, increases as the angular speed of induction motor increases.

Figure 4.10 and 4.11 shows the results of algorithms for motor starting events. Based on these results, we can verify that algorithms precisely detect motor starting events by applying characteristics of motor starting events.

Table 4.8: Results of simulation for motor starting events (phase A)

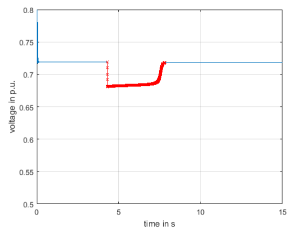
Case	Event Detected	Voltage Sag (p.u.)	Voltage Drop (p.u.)	Duration (s)	Inrush Current (mA)
1	Yes	0.6803	0.0023	7.0583	1497.3959
2	Yes	0.6659	0.0027	4.6250	2014.0840
3	Yes	0.6331	0.0045	2.3667	3201.2595
4	Yes	0.6803	0.0017	7.0667	1499.8659
5	Yes	0.6658	0.0021	4.6333	2017.0134
6	Yes	0.6329	0.0040	2.3667	3204.8028

Table 4.9: Results of simulation for motor starting events (phase B)

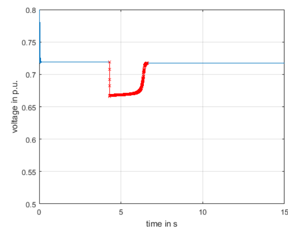
Case	Event Detected	Voltage Sag (p.u.)	Voltage Drop (p.u.)	Duration (s)	Inrush Current (mA)
1	Yes	0.6811	0.0016	7.0667	1501.4221
2	Yes	0.6666	0.0021	4.5833	2027.2719
3	Yes	0.6346	0.0039	2.3500	3237.5606
4	Yes	0.6811	0.0014	7.0667	1499.6009
5	Yes	0.6666	0.0019	4.5833	2025.2270
6	Yes	0.6346	0.0037	2.3583	3235.4863

Table 4.10: Results of simulation for motor starting events (phase C)

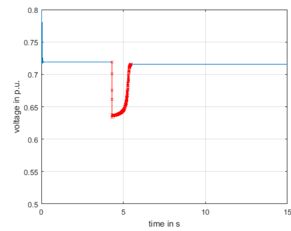
Case	Event Detected	Voltage Sag (p.u.)	Voltage Drop (p.u.)	Duration (s)	Inrush Current (mA)
1	Yes	0.6810	0.0017	7.0250	1204.5450
2	Yes	0.6666	0.0020	4.5917	1685.7937
3	Yes	0.6345	0.0040	2.3333	2889.6821
4	Yes	0.6810	0.0015	7.0250	1203.2834
5	Yes	0.6666	0.0019	4.5917	1684.1250
6	Yes	0.6344	0.0038	2.3333	2887.9291



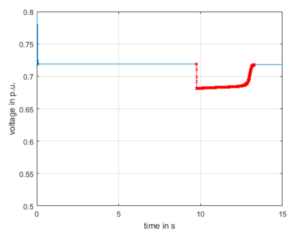
(a) Case 1



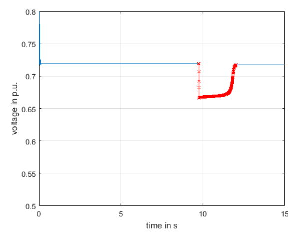
(b) Case 2



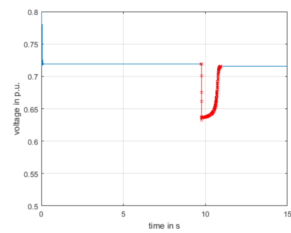
(c) Case 3



(d) Case 4

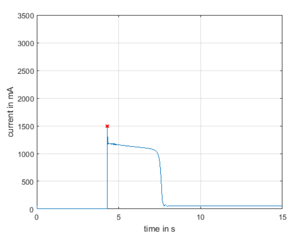


(e) Case 5

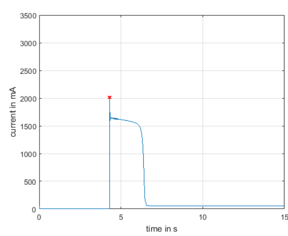


(f) Case 6

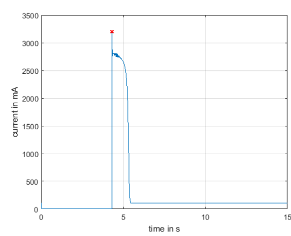
Figure 4.10: RMS voltage of motor starting events



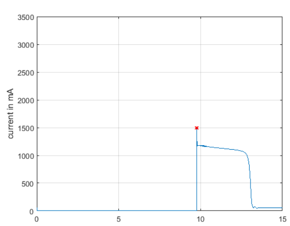
(a) Case 1



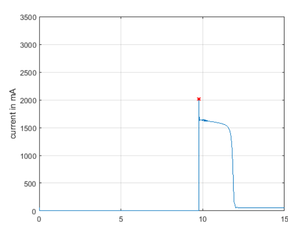
(b) Case 2



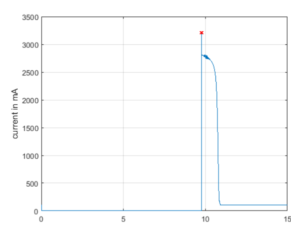
(c) Case 3



(d) Case 4



(e) Case 5



(f) Case 6

Figure 4.11: RMS current of motor starting events

Chapter 5

Application of Detection in Utility Data

In Chapter 4, we run simulations of missing voltage events and motor starting events, and apply the data from simulations to algorithms. Results show that algorithms can detect missing voltage events and motor starting events. The output of algorithms also suggests that the accuracy of algorithms is high. In this section, we will apply utility data to algorithms and analyze the result of the algorithms. Utility data are recorded by monitoring at substations, and this application helps to understand and analyze real events in a power system. We can figure out characteristics of each event by observing the output of algorithms. The first step is to explain utility data which will be applied to algorithms. Next, we detect missing voltage events from the utility data using algorithms. We also analyze output results from algorithms. In the final section of this chapter, we perform detection of motor starting events from this utility data with algorithms and discuss output results. However, there are not many cases of motor starting events available from the utility data. Thus, we apply additional utility data of motor starting events to algorithms to verify the detection of algorithms and analyze the features of motor starting events.

5.1 Overview of Utility Data

Utility data were recorded at three different substations in a real distribution system. Three different substations are labeled as S02, S03, and S04, respectively. There are 962 files monitored simultaneously at each substation. The format of utility data is discussed to explain the data processing part of algorithms in Chapter 3. Each file consists of real values of 3-phase voltage and current. They have 2 types according to the number of recorded data: 250,000 numbers of the real value and 500,000 numbers of the real value. We will apply the entire utility data of each station separately to algorithms for missing voltage events and motor starting events, respectively.

5.2 Results of Missing Voltage Events

The algorithm returns 7 items of each data for missing voltage events. The first column shows the occurrence of missing voltage events for each phase of voltage. If a missing voltage event is detected, it shows 1, and if not, it shows 0. For example, if missing voltage events are detected in all 3 phases, it shows 1;1;1. Similarly, if a missing voltage event is detected on phase B, it shows 0;1;0. The next second to fourth columns labeled fault V_n are the mean value of voltage in each phase during missing voltage events. These columns check that voltage converges to 0 during missing voltage events as the definition of missing voltage event in Chapter 2. The fifth to seventh columns are the duration time of missing voltage events at each phase. The results are as follows.

Table 5.1: Results of S02 for missing voltage events

No.	Phase	Fault V_A (p.u.)	Fault V_B (p.u.)	Fault V_C (p.u.)	Duration V_A (ms)	Duration V_B (ms)	Duration V_C (ms)
1	1;1;1	0.0047	0.01	0.01	2470.08	2493.97	2489.11
2	1;1;1	0.0013	0.0013	0.0008	5062.15	5074.69	5060.05
3	1;1;1	0.197	0.1308	0.2376	3.66	3.78	5.76
4	1;1;1	0.0018	0.0002	0.0011	5.7	5.76	5.34
5	1;1;1	0.0024	0.0001	0.0034	5.82	5.82	5.76
6	1;1;1	0.196	0.1363	0.1576	4.32	4.38	4.26
7	1;1;1	0.0016	0	0.001	5.76	5.76	5.7
8	1;0;1	0.1381	-	0.0488	4.8	-	3.42
9	0;1;0	-	0.1369	-	-	7165.75	-
10	1;1;1	0.0016	0	0.0011	5.7	5.76	5.76
11	1;1;1	0.0016	0	0.0011	5.76	5.76	5.7
12	1;1;1	0.0017	0	0.0011	5.76	5.82	5.76
13	1;1;1	0.0024	0.0001	0.0034	5.76	5.82	5.76
14	1;1;1	0.2561	0.1757	0.1995	4.92	3.96	3.42
15	1;1;1	0.0078	0	0.0011	5.7	5.76	5.76
16	1;1;1	0.0016	0	0.0011	5.76	5.82	5.7

Table 5.2: Results of S03 for missing voltage events

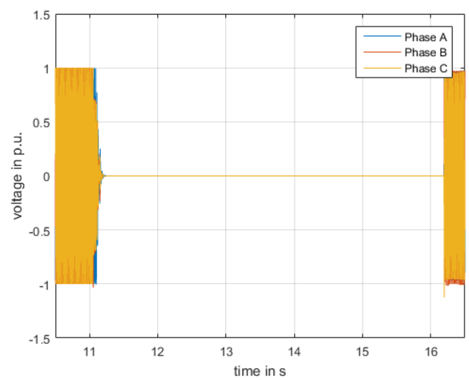
No.	Phase	Fault V_A (p.u.)	Fault V_B (p.u.)	Fault V_C (p.u.)	Duration V_A (ms)	Duration V_B (ms)	Duration V_C (ms)
1	1;1;1	0.0011	0.0008	0.0007	5054.90	5057.18	5047.46
2	1;1;1	0.0019	0.0022	0.0003	5.52	5.36	5.76
3	1;1;1	0.0022	0.0023	0.0002	5.64	5.04	5.04
4	1;1;1	0.0023	0.0103	0.0002	5.64	5.64	5.64
5	1;0;1	0.0022	-	0.0002	5.52	-	5.76
6	1;1;1	0.0022	0.0023	0.0002	5.04	5.40	5.64
7	1;0;1	0.002	-	0.0002	5.52	-	5.52
8	1;1;1	0.0022	0.0024	0.0002	5.64	5.64	5.52
9	1;1;1	0.0022	0.0024	0.0002	5.76	5.64	5.64
10	1;1;1	0.0023	0.0023	0.0002	5.64	5.52	5.64
11	1;1;1	0.0023	0.0101	0.0002	5.64	5.76	5.64
12	1;0;1	0.0021	-	0.0002	5.64	-	5.76
13	1;1;1	0.0022	0.0038	0.0002	5.64	5.76	5.64
14	1;1;1	0.0023	0.0023	0.0002	5.64	5.64	5.64
15	1;1;1	0.088	0.0033	0.1048	5.64	5.48	5.76

Table 5.3: Results of S04 for missing voltage events

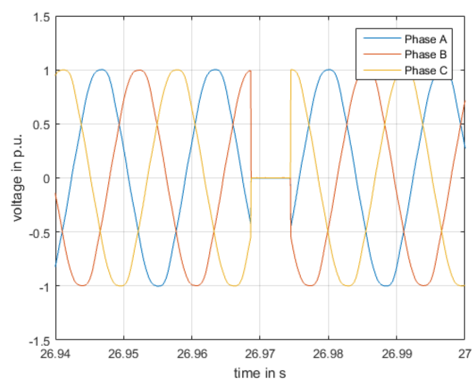
No.	Phase	Fault V_A (p.u.)	Fault V_B (p.u.)	Fault V_C (p.u.)	Duration V_A (ms)	Duration V_B (ms)	Duration V_C (ms)
1	1;1;1	0.0002	0.25	0.0001	5040.26	5037.86	5039.9
2	0;1;0	0.0019	0.0019	0.0019	5.64	5.64	5.64
3	1;1;1	0.0001	0.0021	0.0022	5.28	5.64	5.52
4	1;1;1	0.0002	0.0021	0.0022	5.64	5.64	5.64
5	1;1;1	0.2867	0.002	0.0022	4.2	5.64	5.64
6	1;1;1	0.0021	0.0002	0.0022	5.04	5.76	5.28
7	0;1;0	-	0.0018	-	-	5.64	-
8	1;1;1	0.005	0.002	0.0022	5.52	5.64	5.52
9	1;1;1	0.0049	0.0021	0.0022	5.76	5.64	5.64
10	1;1;1	0.0002	0.0021	0.0022	5.64	5.76	5.64
11	1;1;1	0.0002	0.0021	0.0022	5.64	5.52	5.64
12	0;1;0	-	0.0019	-	-	5.52	-
13	1;1;1	0.0002	0.002	0.0074	5.64	5.52	4.92
14	1;1;1	0.0002	0.0021	0.0144	5.64	5.52	5.76
15	0;1;0	-	0.1041	-	-	5.64	-

As shown in the above 3 tables, 16 missing voltage events in S02, 15 in S03 and 15 in S04 are detected. There are two notable points in the results. The first one is that most of the missing voltage events are instantaneous. Results show that the duration of missing voltage events is mostly about 5 ms, corresponding to instantaneous variations. In the case of S02, only two events, in which durations are more than 30 cycles, are detected. For missing voltage events in which duration is instantaneous, voltage returns to a normal state immediately after events.

Second, results show that most missing voltage events occur on all 3 phases, rather than 1 or 2 phases. Although missing voltage events are detected on one or two phases, voltage of other phases where missing voltage events are not detected is not stable as well.

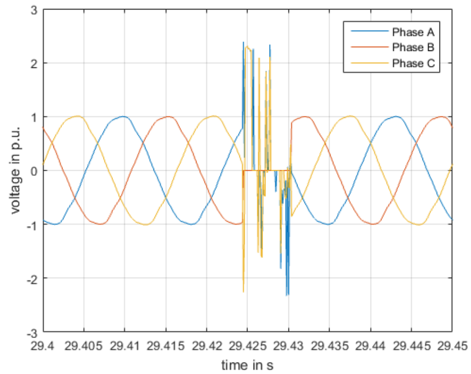


(a) Temporary

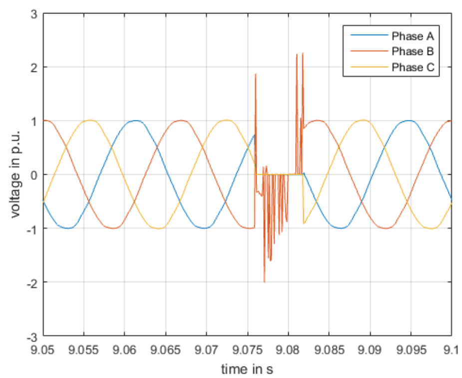


(b) Instantaneous

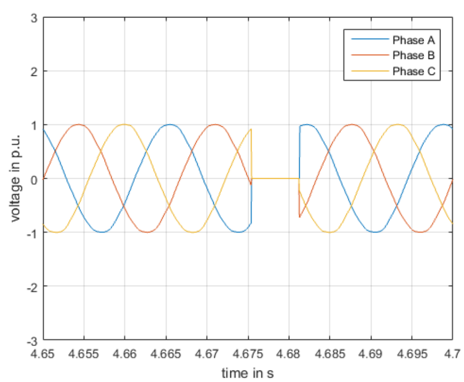
Figure 5.1: Examples of missing voltage events by duration



(a) Detected on one phase



(b) Detected on two phases



(c) Detected on all phases

Figure 5.2: Examples of missing voltage events by phases

5.3 Results of Motor Starting Events

For motor starting events, the algorithm returns 13 features. The first column is the occurrence of motor starting events for each phase. The notation is the same as the first column of results for missing voltage events. The second to fourth columns show the magnitude of voltage sag on each phase. Since the characteristics of motor starting events appear in RMS value, the magnitude of voltage sag is calculated in RMS value. The fifth to seventh columns are the difference between RMS voltage of each phase before motor starting events and after motor starting events. These features check that voltages return to normal state after motor starting events by comparing voltage before events to voltage after events. The eighth to tenth columns are the duration of motor starting events on each phases. The calculation of duration is already explained in Chapter 3. The eleventh to thirteenth features are the peak value of current during events. One of the most notable characteristics of motor starting events is inrush current. These features confirm if there is inrush current during events. The result is as follow.

Table 5.4: Phase and voltage sag of motor starting events

Phase	Voltage sag V_A (p.u.)	Voltage sag V_B (p.u.)	Voltage sag V_C (p.u.)
1;1;1	0.8751	0.8774	0.8982

Table 5.5: Voltage drop of motor starting events

Voltage drop V_A (p.u.)	Voltage drop V_B (p.u.)	Voltage drop V_C (p.u.)
0.005	0.009	0.0107

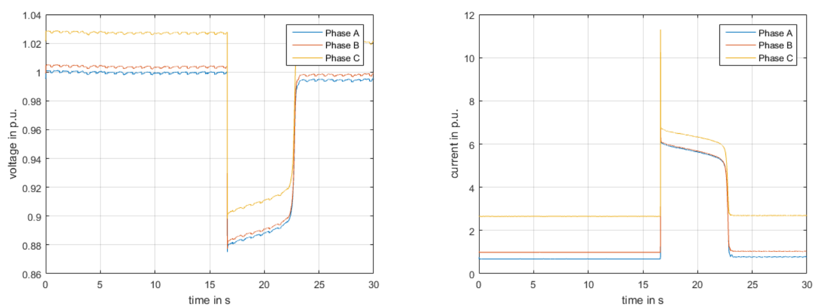
Table 5.6: Duration of motor starting events

Duration V_A (s)	Duration V_B (s)	Duration V_C (s)
6.9958	7	6.9958

Table 5.7: Inrush current of motor starting events

Inrush current I_A (p.u.)	Inrush current I_B (p.u.)	Inrush current I_C (p.u)
7.5157	7.1774	11.2966

One motor starting event is detected. The magnitude of voltage sag is about 0.88 and inrush current, which is more than 7 times normal current, flows. Thus, this event can be regarded as a motor starting event. Additionally, the figures of RMS voltage and current are same as figures of motor starting events. This motor starting event also occurs on all 3 phases, and this balanced occurrence is the characteristic of motor starting.



(a) RMS voltage (b) RMS current

Figure 5.3: An example of motor starting events

Chapter 6

Conclusion

This thesis presents applications of algorithms to detect voltage variation events and calculate their characteristics. From the analysis of results, the objective of detecting voltage variation events is accomplished. Chapter 2 provides the fundamental concept, features and causes of voltage variation. The description of algorithms to detect specific voltage variation events is provided in Chapter 3. Using features of voltage variation events, missing voltage events and motor starting events, the algorithms are developed. In Chapter 4, simulation data from PSCAD/EMTDC are applied to the algorithms. Comparing simulation setting to the results of the algorithms, the performance of the algorithms is verified. This process provides confidence that the results of the algorithms are reasonable. In Chapter 5, an analysis of the results is provided by applying actual field data to algorithms. The results of the algorithms are evaluated for missing voltage events and motor starting events, respectively.

Bibliography

[1] IEEE recommended practice for powering and grounding electronic equipment. *IEEE Std 1100-1999*, pages 1–408, Sept 1999.

[2] IEEE recommended practice for monitoring electric power quality. *IEEE Std 1159-2009 (Revision of IEEE Std 1159-1995)*, pages c1–81, June 2009.

[3] Seon-Ju Ahn, Dong-Jun Won, D-Yop Chung, and Seung-U Moon. Determination of the relative location of voltage sag source according to event cause. In *Power Engineering Society General Meeting, 2004. IEEE*, pages 620–625 Vol.1, June 2004.

[4] B. Bae, J. Jeong, J. Lee, and B. Han. Novel sag detection method for line-interactive dynamic voltage restorer. *IEEE Transactions on Power Delivery*, 25(2):1210–1211, April 2010.

[5] Math HJ Bollen. The influence of motor reacceleration on voltage sags. *IEEE Transactions on Industry Applications*, 31(4):667–674, 1995.

[6] Math HJ Bollen, Mats Hager, and Christian Roxenius. Effect of induction motors and other loads on voltage dips: theory and measurements. In *Power Tech Conference Proceedings, 2003 IEEE Bologna*, volume 3, pages 6–pp. IEEE, 2003.

[7] M.H. Bollen. *Understanding Power Quality Problems: Voltage Sags and Interruptions*. IEEE - TP 139-0. Wiley, 2000.

[8] MHJ Bollen and PME Dirix. Simple model for post-fault motor behaviour for reliability/power quality assessment of industrial power systems. *IEE Proceedings-Generation, Transmission and Distribution*, 143(1):56–60, 1996.

[9] S. Chapman. *Electric Machinery Fundamentals*. Electric machinery fundamentals. McGraw-Hill Companies,Incorporated, 2005.

[10] F. B. Costa and J. Driesen. Assessment of voltage sag indices based on scaling and wavelet coefficient energy analysis. *IEEE Transactions on Power Delivery*, 28(1):336–346, Jan 2013.

[11] K. Ding, K. W. E. Cheng, X. D. Xue, B. P. Divakar, C. D. Xu, Y. B. Che, D. H. Wang, and P. Dong. A novel detection method for voltage sags. In *2006 2nd International Conference on Power Electronics Systems and Applications*, pages 250–255, Nov 2006.

[12] R.C. Dugan, S. Santoso, M.F. McGranaghan, and H.W. Beaty. *Electrical power systems quality*. McGraw-Hill professional engineering. McGraw-Hill, 2003.

[13] D. Gallo, C. Landi, and M. Luiso. Accuracy analysis of algorithms adopted in voltage dip measurements. *IEEE Transactions on Instrumentation and Measurement*, 59(10):2652–2659, Oct 2010.

[14] J.D. Glover, M.S. Sarma, and T. Overbye. *Power System Analysis and Design*. Cengage Learning, 2011.

[15] Luis Guasch, Felipe Córcoles, and Joaquín Pedra. Effects of symmetrical and unsymmetrical voltage sags on induction machines. *IEEE Transactions on power delivery*, 19(2):774–782, 2004.

[16] W. Kanitpanyacharoean and S. Premrudeepreechacharn. Power quality problem classification using wavelet transformation and artificial neural networks. In *Power Systems Conference and Exposition, 2004. IEEE PES*, pages 1496–1501 vol.3, Oct 2004.

[17] M. Kezunovic and Y. Liao. A novel method for equipment sensitivity study during power quality events. In *Power Engineering Society Winter Meeting, 2000. IEEE*, volume 2, pages 993–998 vol.2, 2000.

[18] R. Naidoo and P. Pillay. A new method of voltage sag and swell detection. *IEEE Transactions on Power Delivery*, 22(2):1056–1063, April 2007.

[19] A.V. Oppenheim and R.W. Schafer. *Discrete-time Signal Processing*. Prentice-Hall signal processing series. Pearson, 2010.

[20] S. Santoso. *Fundamentals of Electric Power Quality*. CreateSpace Independent Publishing Platform, 2010.

[21] E. Styvaktakis, M. H. J. Bollen, and I. Y. H. Gu. Expert system for classification and analysis of power system events. *IEEE Transactions on Power Delivery*, 17(2):423–428, Apr 2002.

[22] N. S. Tunaboylu, E. R. Collins, and P. R. Chaney. Voltage disturbance evaluation using the missing voltage technique. In *Harmonics and Quality of Power Proceedings, 1998. Proceedings. 8th International Conference On*, volume 1, pages 577–582 vol.1, Oct 1998.

[23] F. Velez. Open conductor analysis and detection. In *2014 IEEE PES General Meeting — Conference Exposition*, pages 1–7, July 2014.

[24] DA Woodford. PSCAD user's guide. *Manitoba HVDC Research Centre*, 2003.