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Efficient On-Line Detection Scheme of Voltage Events Using Quadrature Method

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***Abstract*—Short-duration RMS voltage variations, namely sag, swell and interruption, are characterized by the variations of RMS voltage values and time durations. In this paper, the quadrature method for calculating RMS voltage is used to efficiently detect these power quality events. For comparison, the same power quality events are detected using conventional RMS calculation methods. Different voltage events are simulated and the results of the quadrature and conventional methods are compared. An experimental real-time monitoring system for voltage events based on the LabVIEW platform is built, and several voltage events are tested and evaluated by the developed setup using quadrature and conventional methods. Both simulation and experimental results validates the superiority of the quadrature method for most of the considered scenarios in terms of accuracy and robustness.**

***Index Terms*—LabVIEW, power quality, quadrature method, rms calculation methods, voltage events,**

I. INTRODUCTION

Interruptions, sags and swells are power quality phenomena that involve short duration RMS voltage variation in supply voltage. The recurrence and consequences of these phenomena has great economic impact on industrial end users (e.g. in the operation of smart grids [1], islanded microgrids [2] and adjustable speed drives [3]).

The IEEE Standard 1159-2009 [4] and the IEC standard 61000-4-30 [5] define a short-duration root-mean-square (RMS) voltage variation as a variation of the RMS value of the voltage from the nominal for a time greater than half a cycle but less than or equal to 1 minute. A short-duration voltage variations can be described as an interruption (decrease to less than 10% of nominal), a sag (decrease to the range between 10% and 90% of nominal) or a swell (increase above 110% of nominal).

RMS computation algorithms are commonly used in automatic detection, characterization and classification of power quality events including voltage sag, swell and interruption [1], [6]-[9]. It has been shown that specification of the RMS calculation method is critical in determining the time and magnitude of these events [10], [11].

For conventional RMS calculation methods, the most important factors that affect the results are the time window length and the time interval for updating RMS values [12, 13, 14]. Although the use of discrete RMS voltage measurements instead of saving the actual voltage waveforms is memory-efficient [7], processing a large number of discrete samples slows down the execution of these methods [2].

The faster quadrature RMS calculation method was developed in [15] where only four samples per period were used for estimating the RMS measurement. Furthermore, it was shown that the quadrature method can be implemented using two samples in one half cycle of each period [16].

This paper explores the accuracy, robustness and efficiency of the quadrature method compared to widely used conventional methods. Different scenarios of short-duration voltage variations are considered. The simulation and experimental real-time results obtained using the quadrature method and conventional RMS-based methods are compared. This paper is organized as follows: The conventional RMS calculation methods are briefly described in section II, followed by an overview of the quadrature method in Section III. The experimental setup is presented in section IV. The simulation results and the experimental results are provided in section V and VI respectively. Finally, the conclusion is drawn in section VII.

II. CONVENTIONAL RMS CALCULATION METHODS

The RMS value of a voltage waveform sampled N times per waveform cycle is generally given by

$$V_{\text{rms}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} v_i^2} \tag{1}$$

where v_i is the sampled voltage at time $(i-1)\,\Delta t$, and Δt is the sampling period.

For a sinusoidal voltage waveform, the RMS value can be calculated either form one full waveform cycle (i.e. N samples) or from one half of the waveform cycle (i.e. $N/2$ samples). Also, after each calculation, the sliding window used in the sampling process can be moved along the waveform by one sampling period (Δt), half a waveform cycle ($N/2$, Δt), or full waveform cycle (N, Δt). The various calculation methods are graphically explained in

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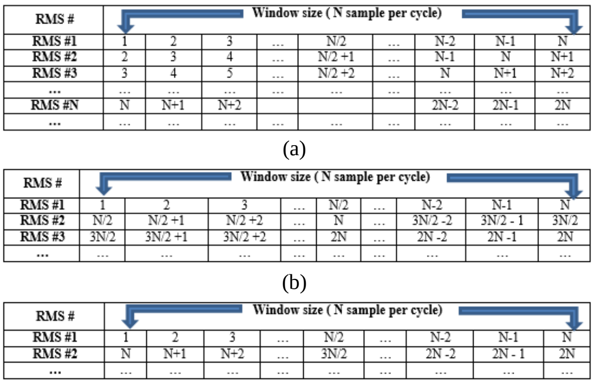
Fig. 1 for full-cycle sampling window and Fig. 2 for half-cycle sampling window.

The time length of the sampling window and the sliding time interval significantly affect the calculation and updating of voltage RMS values. The majority of currently available monitoring devices depend on RMS values to detect variations in the voltage magnitude [17], [18].



RMS #	Window size (N sample per cycle)								
RMS #1	1	2	3	…	N/2	…	N-2	N-1	N
RMS #2	2	3	4	…	N/2 +1	…	N-1	N	N+1
RMS #3	3	4	5	…	N/2 +2	…	N	N+1	N+2
…	…	…	…	…	…	…	…	…	…
RMS #N	N	N+1	N+2				2N-2	2N-1	2N
…	…	…	…	…	…	…	…	…	…

(a)

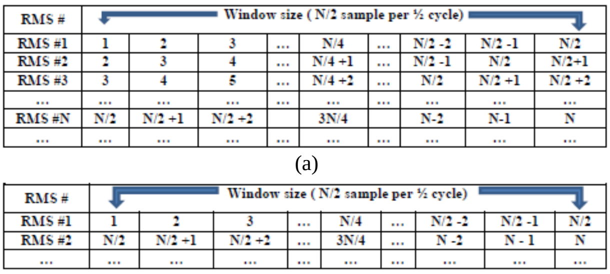
RMS #	Window size (N sample per cycle)								
RMS #1	1	2	3	…	N/2	…	N-2	N-1	N
RMS #2	N/2	N/2 +1	N/2 +2	…	N	…	3N/2 -2	3N/2 - 1	3N/2
RMS #3	3N/2	3N/2 +1	3N/2 +2	…	2N	…	2N -2	2N -1	2N
…	…	…	…	…	…	…	…	…	…

(b)

RMS #	Window size (N sample per cycle)								
RMS #1	1	2	3	…	N/2	…	N-2	N-1	N
RMS #2	N	N+1	N+2	…	3N/2	…	2N -2	2N - 1	2N
…	…	…	…	…	…	…	…	…	…

(c)

Fig. 1. Sliding window methods for calculating the rms values with sampling window N samples: (a) Sample to sample sliding, (b) Half-cycle sliding, and (c) One cycle sliding.



RMS #	Window size (N/2 sample per ½ cycle)								
RMS #1	1	2	3	…	N/4	…	N/2 -2	N/2 -1	N/2
RMS #2	2	3	4	…	N/4 +1	…	N/2 -1	N/2	N/2+1
RMS #3	3	4	5	…	N/4 +2	…	N/2	N/2 +1	N/2 +2
…	…	…	…	…	…	…	…	…	…
RMS #N	N/2	N/2 +1	N/2 +2		3N/4		N-2	N-1	N
…	…	…	…	…	…	…	…	…	…

(a)

RMS #	Window size (N/2 sample per ½ cycle)								
RMS #1	1	2	3	…	N/4	…	N/2 -2	N/2 -1	N/2
RMS #2	N/2	N/2 +1	N/2 +2	…	3N/4	…	N -2	N - 1	N
…	…	…	…	…	…	…	…	…	…

(b)

Fig. 2. Measuring rms values with Half- cycle sample window: (a) Sample to sample sliding and (b) Half-cycle sliding window.

III. QUADRATURE METHOD

The quadrature RMS calculation method uses two samples in each waveform half-cycle with 90 degrees shift between the two samples [16], [19], [20]. This sampling is shown if Fig. 3.

For a pure sinusoidal voltage waveform, at time t1 the sampled voltage will be

$$v(t_1) = V_p \sin(\omega t_1) \tag{2}$$

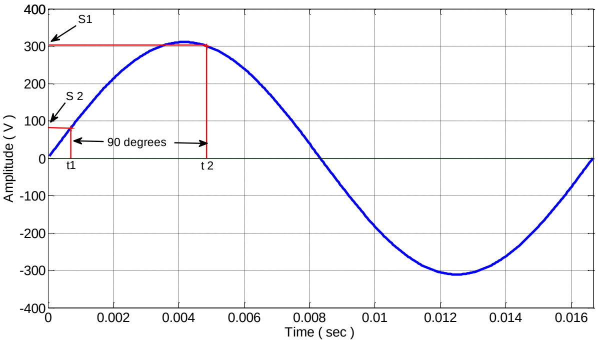


Fig. 3. Two samples per half-cycle used by the proposed method.

And at time $t_2 = t_1 + \pi/2$ (i.e. 90^0 shift) the sampled voltage will be

$$v(t_2) = V_p \sin(\omega t_2) = V_p \sin\left(\omega t_1 + \frac{\pi}{2}\right) = V_p \cos(\omega t_2) \tag{3}$$

The quadrature method utilizes the fact that

$$v^2(t_1) + v^2(t_2) = V_p{}^2\left(\sin^2(\omega t_1) + \cos^2(\omega t_1)\right) \tag{4}$$

Using equation (4), the RMS value of the voltage waveform in consideration can be calculated as

$$V_{\text{RMS}} = \frac{V_p}{\sqrt{2}} = \frac{\sqrt{v^2(t_1) + v^2(t_2)}}{\sqrt{2}} \tag{5}$$

where $v(t)$, V_p and V_{RMS} are the instantaneous, peak and RMS values of the voltage waveform respectively. In this paper, equation (5) is used to detect the power quality events of voltage sag, voltage swell and voltage interruption.

IV. EXPERIMENTAL SETUP

In order to validate the results of this paper, several simulations were implemented in MATLAB and an experimental real-time monitoring system for voltage events was developed using LabView platform.

Fig. 4. The experimental setup in a power quality laboratory.

The experimental setup consists of four major components [15], as shown in Fig. 4:

- LabView platform: offers a graphical programming approach and an easy way to configure off-the-shelf hardware from National Instruments.
- CompactRIO (cRIO): includes a real-time controller, a reconfigurable FPGA chassis, and the input/output modules NI-9225 and NI-9227.
- Programmable AC source: provides the three-phase voltage waveforms with the capability to simulate power line disturbance conditions such as interruption, sag, and swell.
- Programmable electronic loads: simulates real-world load conditions under high crest factor and varying power factors with real-time compensation.

The NI-9225 module is capable of measuring the line voltage up to a maximum of 300 V RMS. The NI-9227 is a 4 channel current measurement module capable of measuring currents up to a maximum 5 A RMS. In this setup, the currents drawn by the connected loads exceed 5 A RMS current, therefore 100/5 A current transformers are used in order to be able to measure the load currents by the module.

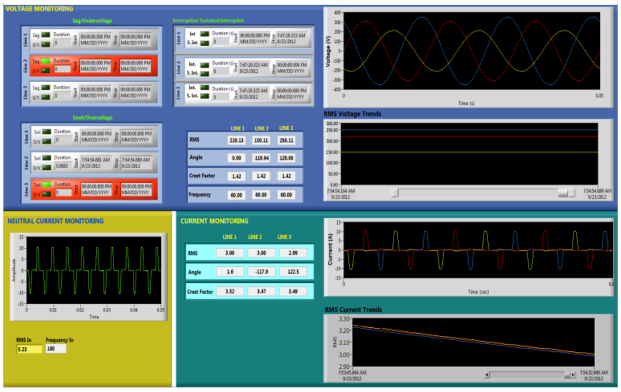


Fig. 5. The monitoring screen of the power quality system.

The ultimate front panel screen for monitoring the power quality system is shown in Fig. 5. The front panel displays information regarding the power quality event type, starting time, ending time, duration, RMS voltage value and the phase in which the event occurred.

V. SIMULATION RESULTS AND DISCUSSIONS

MATLAB was used to simulate three power quality events: voltage sag, voltage interruption and voltage swell. Identification of these events was performed using the half-cycle sampling window method, the full-cycle sampling method, and the quadrature method. The frequency of the waveform was selected to be 60 Hz. The duration of each of the events was 6 cycles (100 ms), and the sampling rate was 166 samples per cycle.

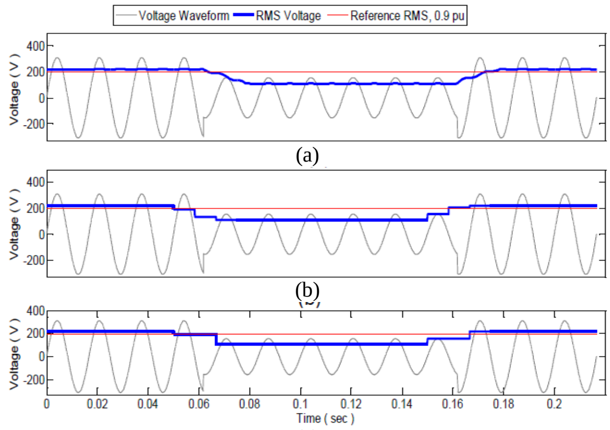
A. *Voltage Sag Event*

A voltage sag is defined as a decrease in the RMS value of the voltage to a value between 10% and 90% of the nominal value for a time greater than half a cycle but less than or equal to 1 minute [4]. For the purpose of this study, the voltage magnitude was reduced by 50% during the simulated 6-cycle sag event.

The conventional RMS calculation methods discussed in Section 2 were used to calculate the RMS value of the voltage waveform before, during and after the sag event. For the following simulations, the sag event was started at the zero-cross point of the instantaneous voltage waveform.

Event detection using full-cycle sampling window was performed with three sliding time intervals: one sample sliding, half-cycle sliding and one cycle sliding. The obtained results are shown in Fig. 6. It is observed that the best result for this method was achieved by the one sample sliding where the sag event was estimated to last for 108.24 ms, adding an error of 8.24 ms to the actual 100 ms event duration. The results for the half-cycle sliding and one cycle sliding were 108.34 ms and 116.67 ms respectively.

Similarly, half-cycle sampling window was used to detect the same event, and the calculations were performed with two sliding time intervals: one sample sliding and half-cycle sliding. Again, the best result for this method was achieved by the one sample sliding where the sag event was estimated to last for 105.65 ms with an error of 5.65 ms.

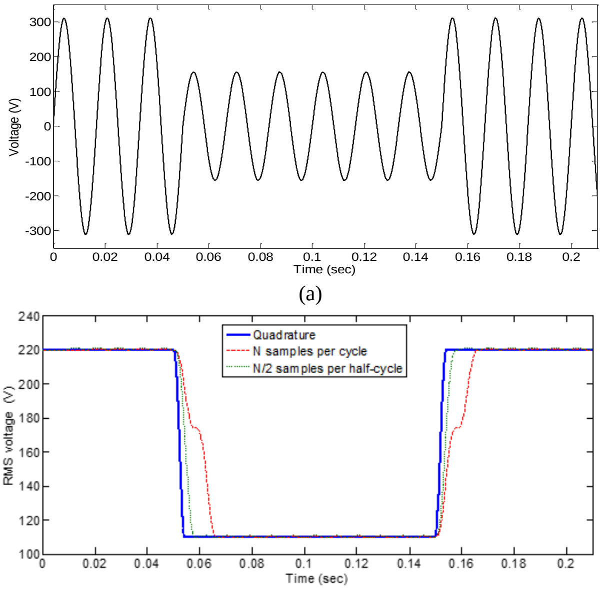


(a)

(b)

(c)

Fig. 6. Detecting a sag event with a full-cycle sampling window (N samples): (a) sample to sample sliding, (b) half-cycle sliding, and (c) one cycle sliding.



(a)

(b)

Fig. 7. RMS value calculation methods with sample sliding approach for voltage sag: (a) Instantaneous waveform and (b) rms voltage track.

Finally, the quadrature method with a sliding time interval of one sample was used to calculate the RMS values and detect the sag event. The quadrature method outperformed the conventional methods by estimating the event duration to be 101.34 ms with an error of only 1.34 ms.

A smaller sliding time intervals produce better results. Therefore the remainder of the simulations and experiments in this paper were performed using the sample to sample sliding window. Fig 7 compares the performance of the three methods when using the sample to sample sliding window.

The voltage sag detection simulation was repeated to test the performance of the three methods for different starting points of the instantaneous voltage waveform. In each test, the starting time was incremented by 15^0 (694.44 µs) and the results were recorded in Table I.

Clearly, the quadrature method achieved the best results for all starting times of the voltage sag. In fact, the worst error of the quadrature method (1.44 ms) was less than the best errors of the other two methods (2.09 ms and 8.20 ms.) In addition, the average error for the quadrature method was 1.39 ms with a standard deviation of 0.05. This demonstrates the robustness and detection accuracy of the quadrature method.

The results recorded in Table I show that the quadrature method produces its maximum error if the voltage sag event begins close to a positive peak or a negative peak of the sinusoidal voltage signal. As demonstrated in Fig. 8, a sag event beginning at a positive peak of the signal will generate a few ripples in the calculated RMS value near the starting and ending times of the event.

However, the impact of these ripples on event detection is minimal since the error in the estimated duration is only 1.44 ms which is a better result than the best results of the conventional methods.

TABLE I: COMPARISON BETWEEN THE ACHIEVED RESULTS OF THE METHODS FOR VOLTAGE SAG

Electrical degrees from cross zero point of instantaneous voltage waveform	RMS calculation methods		
	Quadrature (ms)	*N*/2 samples per half-cycle (ms)	*N* samples per cycle (ms)
0	101.34	102.09	108.20
15	101.34	102.13	108.20
30	101.34	102.09	108.24
45	101.39	102.18	108.24
60	101.44	102.64	108.24
75	101.44	105.84	108.29
90	101.44	106.07	109.08
105	101.44	105.79	108.29
120	101.44	102.64	108.24
135	101.39	102.18	108.24
150	101.34	102.13	108.24
165	101.34	102.13	108.24
180	101.34	102.09	108.20
195	101.34	102.13	108.20
210	101.34	102.09	108.24
225	101.39	102.18	108.24
240	101.44	102.64	108.24
255	101.44	105.84	108.29
270	101.44	106.07	109.08
285	101.44	105.79	108.29
300	101.44	102.64	108.24
315	101.39	102.18	108.24
330	101.34	102.13	108.24
345	101.34	102.13	108.24
Best	101.34	102.09	108.20
Worst	101.44	106.07	109.08
Average	101.39	103.16	108.31
Standard deviation	0.05	1.63	0.24

B. Voltage Interruption Event

A voltage interruption is defined as a decrease in the RMS value of the voltage to a value less than 10% of the nominal value for a time greater than half a cycle but less than or equal to 1 minute [4]. For the purpose of this study, the voltage magnitude was reduced to zero volts during the simulated 6-cycle sag event.

The three RMS calculation methods where tested using the sample to sample sliding window and assuming the interruption event started at the zero-cross point of the instantaneous voltage waveform. The results demonstrate the faster response of the quadrature method in identifying the interrupt event compared to the other methods.

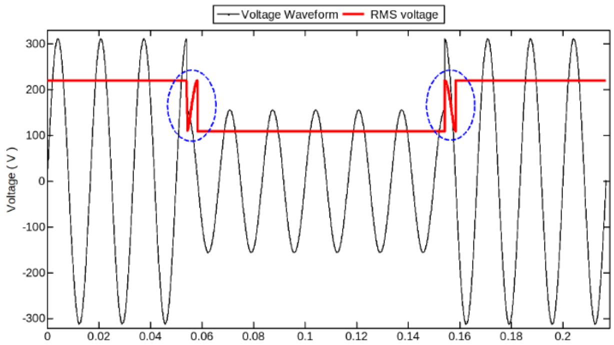


Fig. 8. Quadrature method with voltage sag starting at waveform peak.

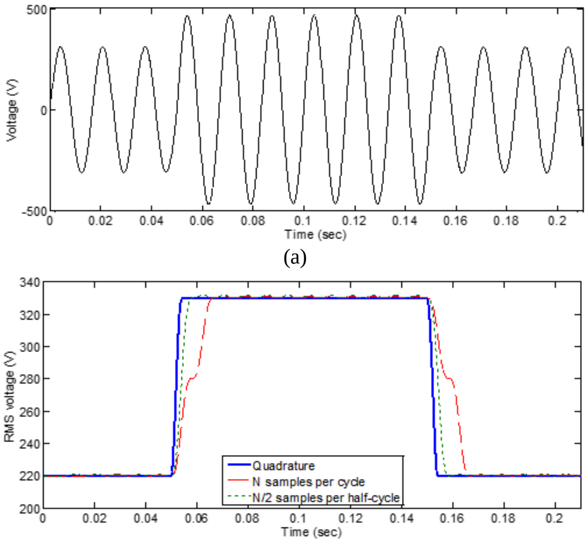
The performance of the three methods in detecting voltage interruption with different starting points of the instantaneous voltage waveform was tested. In each simulation, the starting time was incremented by 15^0 (694.44 μs) and the results were recorded in Table II. The quadrature method achieved the best results for all starting times with an average error of 1.85 ms and a standard deviation of 0.03. The worst error of the quadrature method (1.90 ms) was less than the best errors of the other two methods (2.78 ms and 9.31 ms.)

TABLE II: COMPARISON BETWEEN THE ACHIEVED RESULTS OF THE METHODS FOR VOLTAGE INTERRUPTION

Electrical degrees from cross zero point of instantaneous voltage waveform	RMS calculation methods		
	Quadrature (ms)	*N*/2 samples per half- cycle (ms)	*N* samples per cycle (ms)
0	101.81	102.83	109.31
15	101.81	102.78	109.31
30	101.85	102.83	109.35
45	101.85	102.97	109.35
60	101.85	105.65	109.49
75	101.90	106.58	110.05
90	101.90	106.72	113.01
105	101.90	106.58	110.00
120	101.85	105.60	109.49
135	101.85	102.97	109.35
150	101.85	102.83	109.31
165	101.81	102.78	109.31
180	101.81	102.83	109.31
195	101.81	102.78	109.31
210	101.85	102.83	109.35
225	101.85	102.97	109.35
240	101.85	105.65	109.49
255	101.90	106.58	110.05
270	101.90	106.72	113.01
285	101.90	106.58	110.00
300	101.85	105.60	109.49
315	101.85	102.97	109.35
330	101.85	102.83	109.31
345	101.81	102.78	109.31
Best	101.81	102.78	109.31
Worst	101.90	106.72	113.01
Average	101.85	104.26	109.76
Standard deviation	0.03	1.73	1.03

C. Voltage Swell Event

A voltage swell is defined as an increase in the RMS value of the voltage to a value above 110% of the nominal value for a time greater than half a cycle but less than or equal to 1 minute [4]. For the purpose of this study, the voltage magnitude was increased to 150% of the nominal voltage during the simulated 6-cycle sag event.



(a)

(b)

Fig. 9. RMS calculation methods with sample sliding approach for voltage swell: (a) Instantaneous waveform and (b) rms voltage track.

TABLE III: COMPARISON BETWEEN THE ACHIEVED RESULTS OF THE METHODS FOR VOLTAGE SWELL

Electrical degrees from cross zero point of instantaneous voltage waveform	RMS calculation methods		
	Quadrature (ms)	*N*/2 samples per half- cycle (ms)	*N* samples per cycle (ms)
0	100.14	100.42	103.38
15	100.14	100.42	103.38
30	100.14	100.46	103.29
45	100.19	100.46	100.97
60	100.23	100.51	100.74
75	100.23	100.60	100.70
90	100.23	102.97	100.60
105	100.23	100.60	100.70
120	100.23	100.51	100.79
135	100.19	100.46	101.02
150	100.14	100.46	103.29
165	100.14	100.46	103.43
180	100.14	100.42	103.38
195	100.14	100.42	103.38
210	100.14	100.46	103.29
225	100.19	100.46	100.97
240	100.23	100.51	100.74
255	100.23	100.60	100.70
270	100.23	102.97	100.60
285	100.23	100.6	100.70
300	100.23	100.51	100.79
315	100.19	100.46	101.02
330	100.14	100.46	103.29
345	100.14	100.46	103.43
Best	100.14	100.42	100.60
Worst	100.23	102.97	103.43
Average	100.19	100.69	101.81
Standard deviation	0.04	0.70	1.30

Fig. 9 shows the simulation results of the tested methods using the sample to sample sliding window and assuming the swell event started at the zero cross point of the instantaneous voltage waveform. In this case, the quadrature method was the fastest to detect the event.

For voltage swell with different starting points of the instantaneous voltage waveform, Table III shows that the quadrature method was able to estimate the event duration with an average error of 0.19 ms and a standard deviation of 0.04.

Compared to the conventional methods results, the quadrature method was more accurate and robust.

VI. EXPERIMENTAL RESULTS

A. Single Power Quality Event

The experimental setup described in Section 4 was used to compare the performance of the quadrature method in detecting voltage events with two commonly used methods that utilize RMS voltage to detect voltage events:

- The IEEE and IEC method [4], [5] in which the RMS voltage is measured over one cycle starting at zero crossing, and refreshed each half cycle.
- The commercial method used in majority of power quality instruments [21] in which the RMS voltage is measured over one cycle starting at zero crossing, and refreshed every full cycle.

The programmable AC source was used to generate three three-phase 220V, 60 Hz test signals, each of which consisted of 12 cycles. The sampling rate is selected to be 166 sample/cycle (10 kHz). All of the three voltage events to be detected were started at time 50 ms and ended at time 150 ms, producing a true event duration of 6 cycles (100 ms). In addition, the three phase waveform was assumed to be balanced and therefore each voltage event would affect the three phases simultaneously. The obtained results were recorded per phase.

Unlike the Matlab simulations, the quadrature method was implemented with a half-cycle sliding window in order to reduce the computation cost.

Three power quality events were tested: voltage sag, voltage interruption and voltage swell. The results obtained from the three tested methods whereas follows:

1) Voltage Sag Event

The real-time experimental results of voltage sag detection are shown in Fig.10. The instantaneous three-phase waveform is shown in Fig. 10 (a) where the voltage magnitude was reduced to 198 V (0.9 pu) during the sag event. Fig. 10 (b) to Fig. 10d show the RMS voltage track using the quadrature method, IEEE method and commercial method respectively. Both the quadrature and commercial methods detected the starting time at 51 ms and the end time at 157 ms. The IEEE method detected the starting time at 45 ms and the end time at 154 ms.

2) Voltage Interruption Event

For the voltage interruption detection, the real-time experimental results are shown in Fig. 11. The instantaneous three-phase waveform is shown in Fig.11 (a) where the voltage magnitude fell to 22 V (0.1 pu) during the interruption event. Fig. 11 (b) to Fig. 11d show the RMS voltage track using the quadrature method, IEEE method and commercial method respectively. All three methods detected the starting time at 58 ms. The quadrature and commercial methods accurately detected the end time at 150 ms, whereas the IEEE method detected the end time at 141 ms.

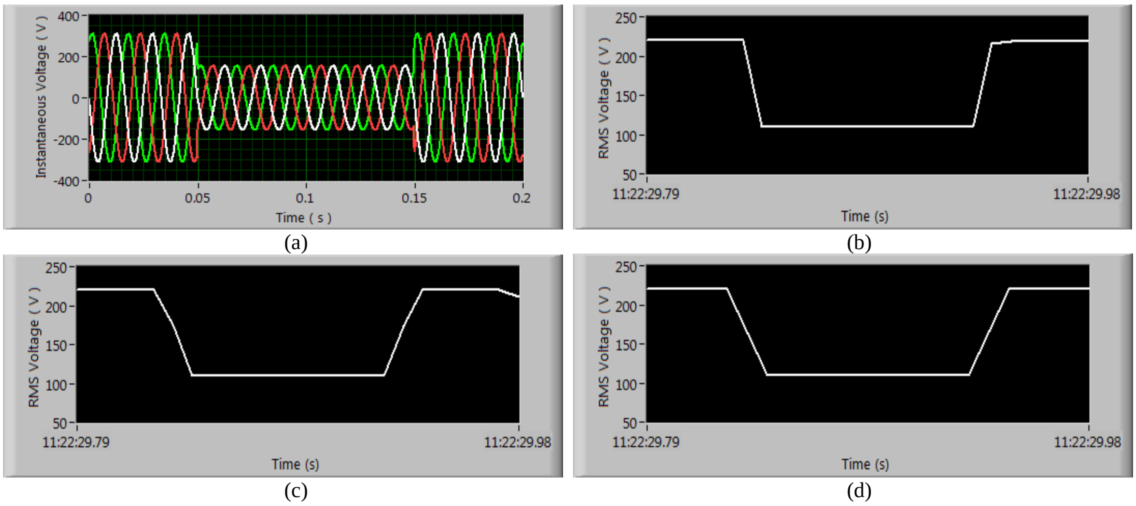


Fig. 10. Voltage sag results: (a) three phase waveform, (b) quadrature method, (c) IEEE method, and (d) commercial method.

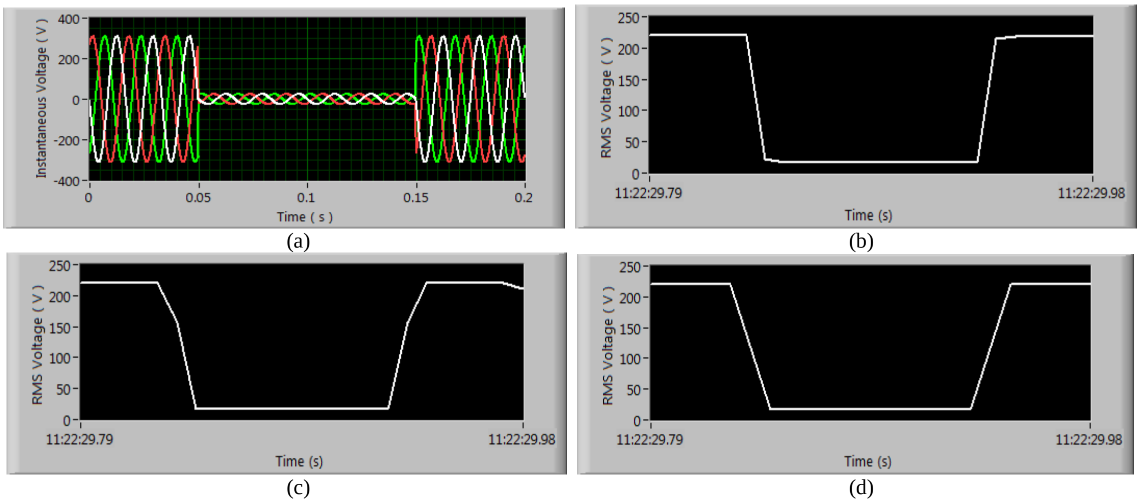


Fig. 11. Voltage interruption results: (a) three phase waveform, (b) quadrature method, (c) IEEE method, and (d) commercial method.

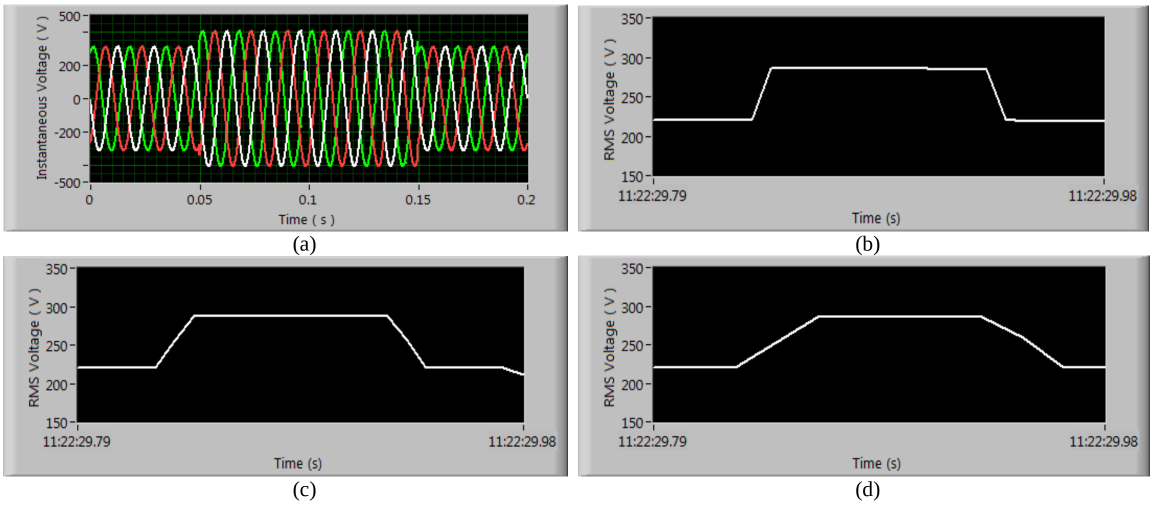


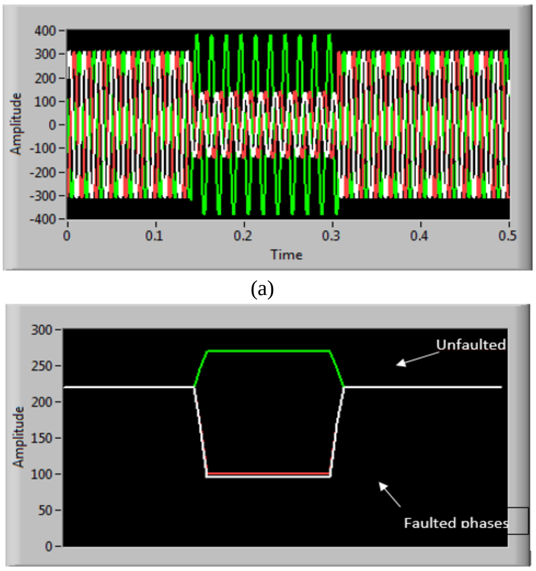
Fig. 12. Voltage swell results: (a) three phase waveform, (b) quadrature method, (c) IEEE method, and (d) commercial method.

3) *Voltage swell event*

Fig. 12 shows the real-time experimental results for the voltage swell detection. The instantaneous three-phase waveform is shown in Fig. 12 (a) where the voltage magnitude was increased to 242 V (1.1 pu) during the swell event. Fig. 12 (b) to Fig. 12 (d) show the RMS voltage track using the quadrature method, IEEE method and commercial method respectively. The quadrature method provided the best start time estimate at 52 ms, followed by the IEEE method at 47 ms, and then the commercial method at 54 ms. The end time was estimated by the IEEE method at 153 ms, by the quadrature method at 155 ms, and by the commercial method at 166 ms.

B. Multiple Power Quality Events

In multi-phase distribution systems, multiple power quality events may affect the system simultaneously. In order to study the performance of the quadrature method during multiple power quality events, a double line-to-ground fault that lasted for 10-cycles was introduced to the experimental setup as shown in Fig.13 (a). The two faulted phases were affected by voltage sag, whereas the unfaulted phase was affected by voltage swell. The results presented in Fig. 13 (b) show that the quadrature method was able to detect the simultaneous multiple voltage events in real-time. In particular, the quadrature method was capable of accurately detected the starting time, ending time, and duration for each of the events in consideration.



(a)

(b)

Fig. 13. Voltages during double line to ground fault: (a) Instantaneous three phase waveform and (b) tracking rms voltage using the quadrature method.

VII. CONCLUSIONS

In this paper, automatic on-line detection power quality events (including voltage sag, swell and interruption) was implemented using the quadrature RMS computation algorithm and using the commonly used RMS-based conventional methods. Simulation results showed the superiority of the quadrature method over the other methods in terms of robustness and detection accuracy. Simulations also showed that a smaller sliding window would provide better results but at higher computational costs. Experimental tests verified the performance of the quadrature method in detecting single voltage events as well as multiple voltage events.

REFERENCES

[1] Ucar, O. F. Alcin, B. Dandil, and F. Ata, “Power quality event detection using a fast extreme learning machine,” *Energies*, vol. 11, no. 1, p. 145, 2018.

[2] N. S. Srivatchan and P. Rangarajan, “Half cycle discrete transformation for voltage sag improvement in an islanded microgrid using dynamic voltage restorer,” *Int. Journal of Power Electronics and Drive System*, vol. 9, no. 1, pp. 25-32, 2018.

[3] G. A. Orcajo, J. M. Cano R., C. H. Rojas G., M. G. Melero, *et al.*, “Analysis of losses due to voltage sags in industrial processes: in uential parameters,” in *Power Quality*, M. P. Donsion and M. I. Buzdugan, Ed. ch. 4, pp. 52-75, Cambridge Scholars Publishing, 2017.

[4] “IEEE recommended practice for monitoring electric power quality," IEEE Standard 1159, 2009.

[5] “Testing and measurement techniques, section 30: Power quality measurement methods,” IEC Standard 61000-4-30, Part 4, 2008.

[6] E. A. Feilat, R. R. Aljarrah, and M. B. Rifai, “Detection and classification of voltage variations using combined envelope-neural network based approach,” *Jordan Journal of Electrical Engineering*, vol. 3, no. 2, pp. 112-124, 2017.

[7] E. Styvaktakis, M. H. J. Bollen, and I. Y. H. Gu, “Automatic classification of power system events using rms voltage measurements,” in *Proc. of IEEE PES Summer Meeting*, 2002, pp. 824-829.

[8] D. Gallo, C. Landi, M. Luiso, and E. Fiorucci, “Survey on voltage dip measurements in standard framework,” *IEEE Trans. on Instrumentation and Measurement*, vol. 63, no. 2, pp. 374-387, 2014.

[9] E. Balouji and O. Salor, “Assessment of rms computation in terms of power quality event detection,” in *Proc. of 23th IEEE Signal Processing and Communications Applications Conf.*, 2015, pp. 2396-2399.

[10] M. Albu and G. T. Heydt, “On the use of rms values in power quality assessment,” *IEEE Trans. on Power Delivery*, vol. 18, no. 4, pp. 1586-1587, 2003.

[11] J. R. Macedo Jr., I. N. Gondim, J. A. F. Barbosa Jr., C. E. Tavares, and A. J. P. Rosentino Jr., “Practical aspects of performance tests on power quality analyzers,” in *Int. Conf. on Renewable Energies and Power Quality*, 2012, pp. 1368-1373.

[12] N. Kagan, E. L. Ferrari, N. M. Matsuo, S. X. Duarte, A. Sanommiya, J. L. Cavaretti, U. F. Castellano, and A. Tenorio, “Influence of rms variation measurement protocols on electrical system performance indices for voltage sags and swells,” in *Proc. of 9th Int. Conf. on Harmonics and Quality of Power*, 2000, pp. 790-795.

[13] A. Moschitta, P. Carbone, and C. Muscas, “Performance comparison of advanced techniques for voltage dip detection,” *IEEE Trans. on Instrumentation and Measurement*, vol. 61, no. 5, pp. 1494-1502, 2012.

[14] P. R. Kamthekar, P. V. Gautam, and R. K. Munje, “Detection, characterization and classification of short duration voltage events using dwt andfuzzy logic,” in *Int. Conf. on Innovative Mechanisms for Industry Applications*, 2017, pp. 242-247.

[15] S. A. Hussain, F. R. Zaro, and M. A. Abido, “Implementation of quadrature based rms calculation on real-time power monitoring systems,” in *Proc. of IEEE Power and Energy Conf. at Illinois*, 2013, pp. 213-217.

[16] F. R. Zaro, M. A. Abido, S. Ameenuddin, and I. M. Elamin, “Characterization of short-duration voltage events,” in *Proc. of IEEE Int. Conf. on Power and Energy*, 2012, pp. 650-654.

[17] M. H. J. Bollen, *Understanding Power Quality Problems: Voltage Sags and Interruptions*, IEEE Press, 2000.

[18] J. Barros and E. Perez, “Limitations in the use of rms value in power quality analysis,” in *Proc. of the IEEE Instrumentation and Measurement Technology Conf.*, 2006, pp. 2261-2264.

[19] J. Howard and H. P. Landgraf, “Quadrature sampling phase detection,” *Review of Scientific Instruments*, vol. 65, no. 6, pp. 2130-2133, 1994.

[20] S. Wetterlin. (2017). A method of using quadrature sampling to measure phase and magnitude. [Online]. Available: www.wetterlin.org/sam/QuadratureSampling

[21] A. Moreno-Munoz, *Power Quality: Mitigation Technologies in a Distributed Environment*, Springer, 2007.

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