Power Quality Events Segmentation in a Voltage Waveform using Joint Triggering Point Detection Scheme

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Abstract - Accurate and timely detection of power quality (PQ) events is imperative for adequate corrective measures to be taken. This paper presents a method of PQ event detection development called joint triggering point detection (JTPD) scheme with a view to achieving a more accurate PQ event detection in a voltage waveform. The JTPD combines the advantage of cumulative sum (CUSUM) algorithm for the statistical distribution of a signal waveform and the discrete wavelet transform (DWT) for change-point detection. The performance of JTPD scheme using detection rate was compared with CUSUM and DWT schemes and based on the analysis, the detection rate of JTPD, CUSUM and DWT were 100%, 95% and 50% respectively. With this, the proposed approach outperformed CUSUM and DWT schemes by 5% and 50% respectively. Hence, the proposed approach is suitable for accurate detection of voltage dip, swell and interruption PQ events

Keywords: Cumulative Sum, Discrete Wavelet Transform, Joint Triggering Point Detection, Power Quality, Voltage Waveform

1 Introduction

Power quality (PQ) is a general term used in describing the quality of voltage and current waveforms. It has become a major concern in power systems owing to the effects of wide use of switched power sources by sensitive power equipment (Bollen, 2003; Leonardo, 2007; Philip, 2004). Poor quality of power supply has greatly reduced life spans of many electronic equipment. Because of this vulnerability, electric utilities and consumers are becoming increasingly concerned about the quality of electricity supply. PQ problems such as sag (or dip), rise or swell, impulses and harmonic distortion result in variety of electrical disturbances which may manifest themselves at various places in the power network and have different effects on various kinds of sensitive loads (Kusko and Thompson, 2007).

The major causes of PQ events include; transformer energizing, motor starting, capacitor energizing, transformer saturation and step change (Bollen et al. 2009). Many researchers have worked on PQ detection and classification over the years using various signal processing techniques (Abdel-Galil, 2004; Antonio et al. 2011). Bollen et al. (2009) investigated the use of root mean squared (RMS) approach for detection of voltage dip events on three phase voltage waveform. Voltage magnitude variations are quantified by the RMS voltage calculated over a 200-ms window. He et al (2010) presented a triggering point detection approach to PQ monitoring in smart grids based on change-point detection theory with unknown parameters. A sequential CUSUM scheme was developed with the aim of providing quick and accurate detection of the occurrence of PQ event in real-time. Santoso et al. (2000) presented electric power quality disturbances detection scheme using wavelet transform analysis for short and fast transient disturbances. Liang, et al. (2002) presented a tool that can be used to evaluate PQ problems, which is based on wavelet decomposition technique.

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The wavelet technique used placed a higher emphasis on transient event instead of a general study of various disturbances. CUSUM and DWT record good a performance in the detection of PQ events, a hybrid of CUSUM and DWT is JTPD; which combines the advantage of the cumulative sum (CUSUM) algorithm for the statistical distribution of a signal waveform and the discrete wavelet transform (DWT) for change-point detection.

This paper, therefore, presents a method of PQ event detection development called joint triggering point detection (JTPD) scheme with a view to achieving a more accurate PQ event detection in a waveform voltage. The rest of this paper is organized as follows: Section 2, presents the materials and methods. Section 3, present the results and discussion. Section 4, presents the conclusion and future recommendation.

2 Materials and Methods

2.1 Modelling of Single-Phase Voltage Signal

An undistorted single-phase voltage signal is in form of a continuous-time waveform signal. This voltage waveform can be expressed as:

$$v(t) = \sqrt{2}V\cos(2\pi f_o t + \phi_o) \quad (1)$$

where V is the rms voltage value, f_o is the fundamental frequency, $\emptyset_o$ is the initial phase of the voltage waveform and t is the time instance. The occurrence of a PQ event can be modelled as an amplitude modulation of the fundamental-frequency voltage, which can be expressed as:

$$v(t) = \sqrt{2}V[1 + d(t)]\cos(2\pi f_o t + \phi_o) \quad (2)$$

where d(t) is the modulating signal given as;

$$d(t) = V_m \cos(2\pi f_m t + \phi_m) \quad (3)$$

Where; V_m the amplitude, f_m the frequency and ϕ_m is the phase of the modulating signal. Combining equations (2) and (3) gives;

$$v_e(t) = \tfrac{1}{2}\sqrt{2}VV_m \cos[2\pi(f_o + f_m)t + \phi_m] + \sqrt{2}V\cos(2\pi f_o t + \phi_o) + \tfrac{1}{2}\sqrt{2}VV_m \cos[2\pi(f_o - f_m)t + \phi_m] \quad (4)$$

This equation consists of the original signal and disturbance which varies in frequency and magnitude. The discrete voltage signal after the occurrence of a PQ event can be expressed as;

$$v_e[k] = A_e \cos(2\pi f_e T_s k + \phi_e) + \varphi[k] \quad (5)$$

where A_e, f_e and ϕ_e are the amplitude, frequency and phase, respectively, and after the occurrence of the PQ event, $\varphi[k]$ is the voltage waveform distortion caused by the PQ events. The synthetic signals used in the analysis were generated using the following parameters as specified in the Table 1;

Table 1. Parameter of Synthetic Signals Used.

S/N	Input parameters	Value Used
1.0	RMS Nominal Voltage (V)	220 Volts
2.0	Fundamental Frequency (f_o)	50Hz
3.0	Sampling rate (f_s) in samples per second	6.4×10^3 (kHz)
4.0	Samples per 50Hz cycle (N cycle)	f_s/f_o
5.0	Window Width	1500 – 3000

2.2 Joint Triggering Point Detection (JTPD) Scheme

The developed JTPD scheme consists of the combination of CUSUM and DWT algorithms. The triggering points detected by CUSUM and DWT are passed to a modified least-square (MLS) operator given by equation (6). Every triggering point supplied by CUSUM (x) is compared with every other triggering point supplied by DWT (y) using the MLS operator. If the MLS value is greater than 10^{-3} threshold (determined by heuristic search), then the point is rejected; however, if the value is less than or equals to 10^{-3}, the point is accepted and the minimum between x and y is taken as the triggering point.

$$MLS = \frac{(x-y)^2}{10^6} \quad (6)$$

The CUSUM method is based on the statistical distribution of the signal before a change and after the change. The log likelihood ratio (LLR) at sample k of a signal waveform can be expressed as:

$$Y[k] = \sum_{j=1}^{k} y[j] \quad (7)$$

with

$$y[j] = \ln \frac{f_{\Theta_1}(s[j])}{f_{\Theta_0}(s[j])} \quad (8)$$

where $f_{\Theta_0}(s)$ is the probability density function (PDF) of signal x before the occurrence of the PQ event, $f_{\Theta_0}(s)$ is the PDF of signal after the occurrence of the PQ event. A change is detected in a signal waveform if the difference between the value of $Y[k]$ and the minimum LLR value from $Y[1]$ to $Y[k]$ is greater than or equal to a predefined threshold. The DWT is efficient for extracting signal features from a signal by decomposing the signal into a number of scales (or levels). The detailed and approximation signals after the first decomposition can be respectively expressed as:

$$d_1[k] = \sum_q h_{LP}[q-2k]x_0[k] \quad (9)$$

and

$$x_1[k] = \sum_q h_{HP}[q-2k]x_0[k] \quad (10)$$

where $d_1[k]$ is the detailed signal, $x_1[k]$ is the approximation signal and h_{LP} is the low-pass filter. The detection of the occurrence of a PQ event in a signal waveform is accepted only if both equations (7) and (9) indicate a change at the same point or sample k. The procedural steps taken in implementing proposed JTPD scheme are as shown in Figure 1.

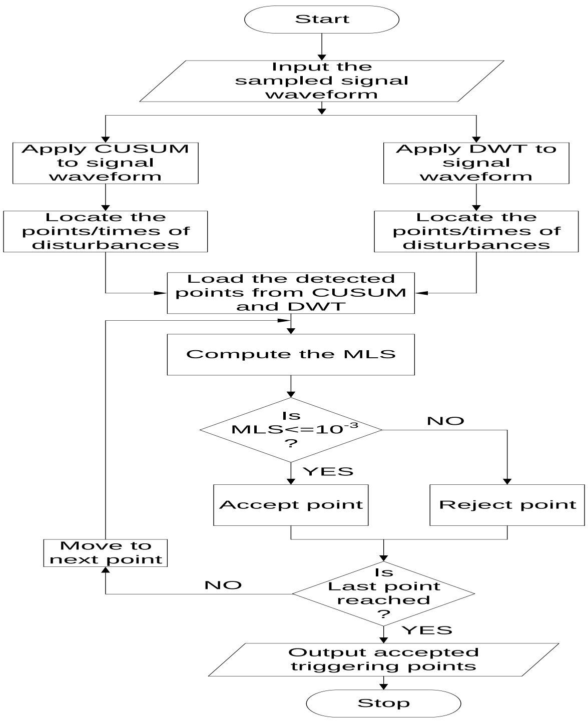


Fig.1: Flow Chat for the Proposed Approach

3 Results and Discussion

Figure 2 shows generated voltage signal waveforms of duration 1 sec (or 100,000 samples) with PQ events. The event window is located between 0.4 sec and 0.8 sec. In Figure 3, the result of detecting PQ event using DWT on a signal waveform containing a voltage swell event is presented. The indicator shows that DWT detected 4 triggering points at 0.4002 sec, 0.4502 sec, 0.7997 sec and 0.8497 sec; this implies that the DWT TPD scheme falsely detected 2 triggering points at 0.4502 sec and 0.8497 sec while the two rightly detected points are 0.4002 sec and 0.7997 sec having errors of 0.0002 sec and 0.0003 sec, respectively. The result of the CUSUM TPD scheme is presented in Figure 4 for the detection of a voltage swell event in the signal waveform. The indicator reveals that the CUSUM identified 3 triggering points in the waveform at 0.0000 sec, 0.4000 sec and 0.8000 sec; this reveals that the first point is falsely detected while the second and third points are rightly without errors.

For the voltage dip event, the DWT TPD scheme was applied to a signal waveform containing a voltage dip event as shown in Figure 5. The indicator shows that DWT detected 10 triggering points at 0.4000 sec, 0.4500 sec, 0.5000 sec, 0.5500 sec, 0.6000 sec, 0.6501 sec, 0.7001 sec, 0.7501 sec, 0.8001 sec and 0.8501 sec; this reveal that eight triggering points are falsely detected and two are rightly detected points at 0.4000 sec and 0.8001 sec with first point having no error while the second point has an error of 0.0001 sec, respectively. Figure 6 presents the TPD result when CUSUM is applied on the signal waveform containing voltage dip event. The indicator reveals that the CUSUM TPD scheme rightly detected the 2 points at 0.4000 sec and 0.8000 sec without errors.

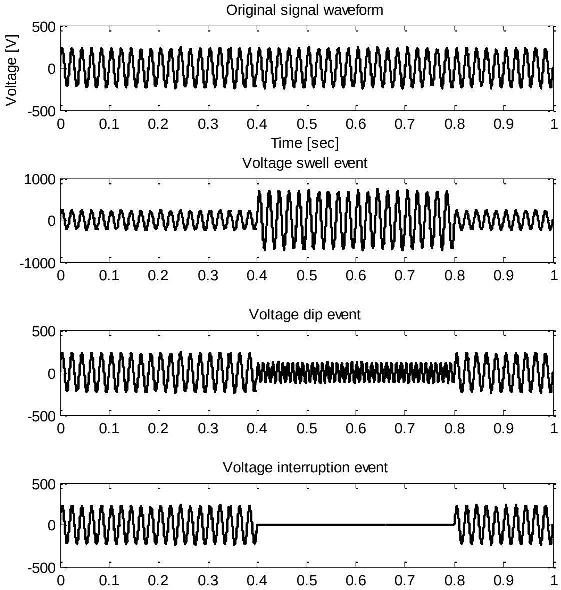


Fig. 2: Generated synthetic voltage signal waveforms with PQ events.

The result of applying the DWT TPD scheme on a signal waveform containing voltage interruption event is shown in Figure 7.

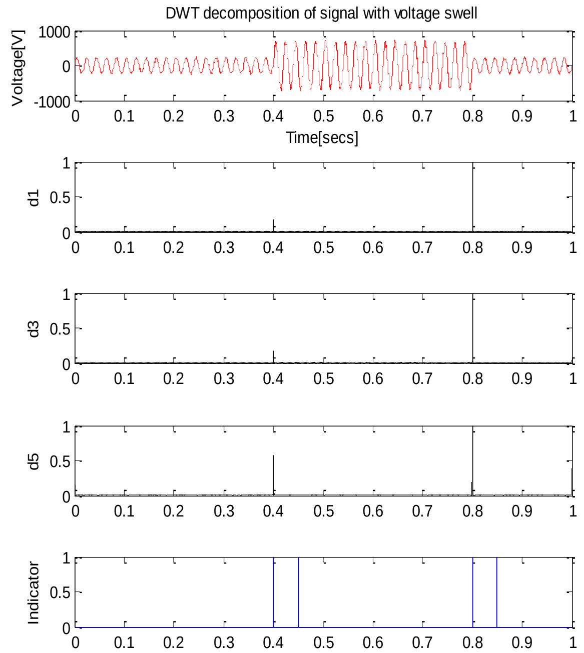


Fig. 3: Application of DWT to a synthetic voltage waveform with voltage swell PQ event.

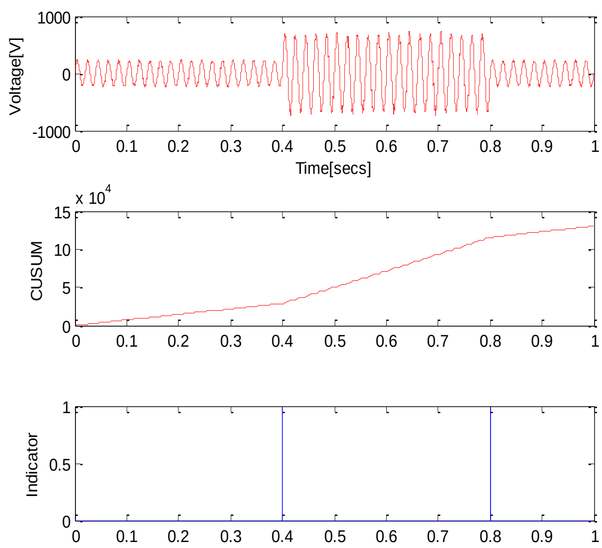


Fig. 4: Application of CUSUM to a synthetic voltage waveform with voltage swell PQ event.

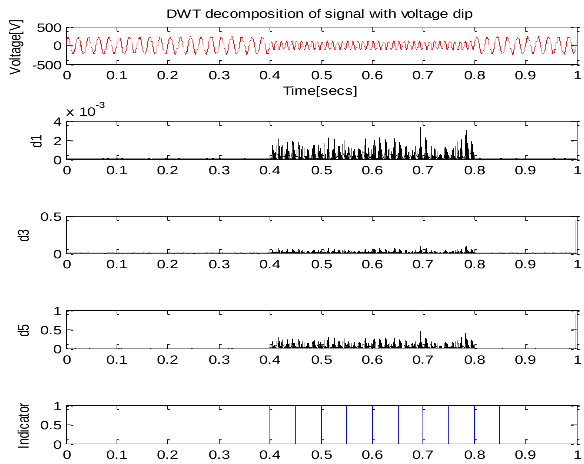


Fig. 5: Application of DWT to a synthetic voltage waveform with voltage dip PQ event.

The indicator reveals that the DWT TPD scheme identified 4 triggering points at 0.4002 sec, 0.5002 sec, 0.7997 sec and 0.8997 sec. The result shows that 2 points (0.5002 sec and 0.8997 sec) are falsely detected while the other 2 points (0.4002 sec and 0.7997 sec) are rightly detected with errors of 0.0002 and 0.0003, respectively.

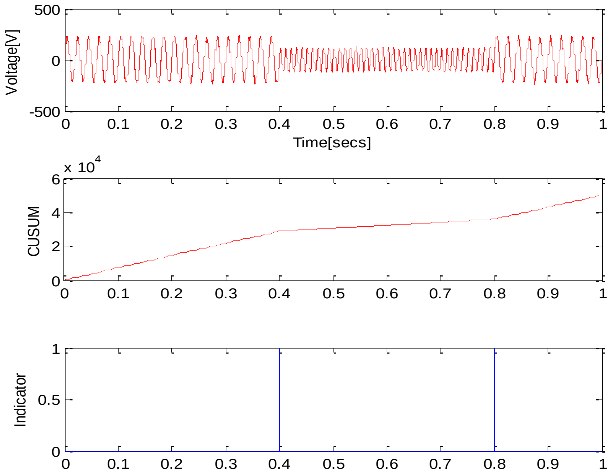
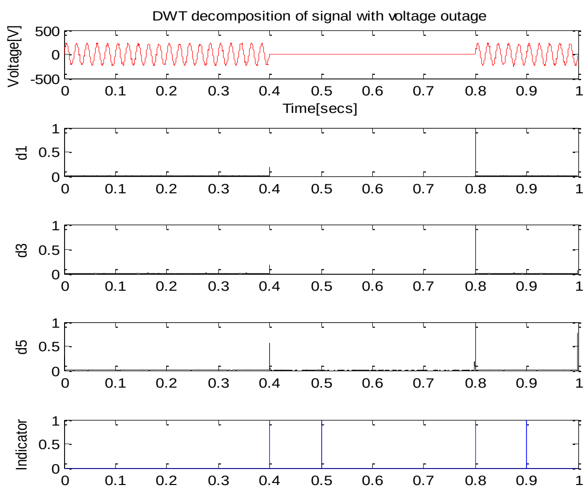


Fig. 6: Application of CUSUM to a synthetic voltage waveform with voltage dip PQ event.

The application of CUSUM TPD scheme on the signal waveform containing voltage interruption event is shown in Figure 8. The CUSUM TPD scheme detected the 2 triggering points rightly at 0.4000 sec and 0.8000 sec without errors



. Fig. 7: Application of DWT to a synthetic voltage waveform with voltage interruption PQ event.

The JTPD scheme consists of both CUSUM and DWT algorithms with the MLS operator. The TPD performances of DWT, CUSUM and JTPD schemes on a signal waveform containing voltage dip are compared in Figure 9. The DWT, CUSUM and JTPD schemes detected 10 points, 2 points and 2 points respectively.

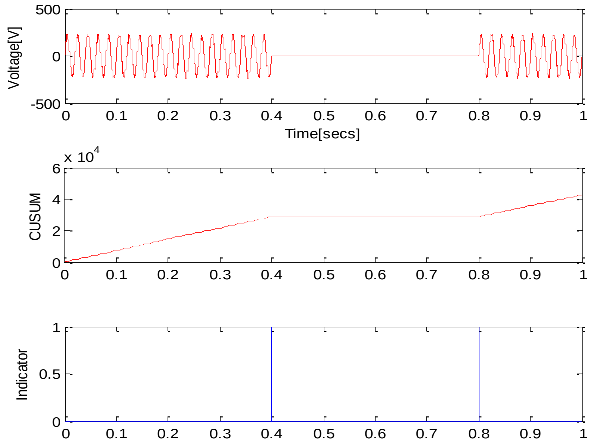


Fig. 8: Application of CUSUM to a synthetic voltage waveform with voltage interruption PQ event.

The DWT falsely detected 8 points while CUSUM and JTPD rightly detected the actual 2 triggering points. The result shows that both the JTPD and CUSUM schemes outperform the DWT scheme for the detection of the voltage dip event. The JTPD scheme achieves this by ranking the outputs of both DWT and CUSUM and then eliminating irreconcilable points.

The results of the TPD schemes on a voltage signal waveform containing a voltage swell event are presented in Figure 10. The indicators reveal that DWT detected 4 points (0.4002 sec, 0.4502 sec, 0.7997 sec and 0.8497 sec), CUSUM detected 3 points (0.0001 sec, 0.4000 sec and 0.8000 sec) while JTPD detected 2 points (0.4000 sec and 0.7997 sec). This shows that the JTPD outperforms both the DWT and CUSUM schemes while the CUSUM gives a better detection than the DWT. The TPD schemes were also compared for the detection of a voltage interruption event in a voltage signal waveform as presented in Figure 11; the results show that the DWT, CUSUM and JTPD detected 4 points (0.4002 sec, 0.5002 sec, 0.7997 sec and 0.8997 sec), 2 points (0.4000 sec and 0.8000 sec) and 2 points (0.4000 sec and 0.7997 sec) respectively. This implies that both the CUSUM and JTPD outperform the DWT scheme; while CUSUM gives the accurate point at which the interruption ends (0.8000 sec) but JTPD has a detection error of 0.0003 sec.

The results show that the detection rate for JTPD is 100%, the CUSUM is 95% while DWT gives 50%. This reveals that the JTPD outperforms the CUSUM and DWT schemes by 5% and 50% respectively.

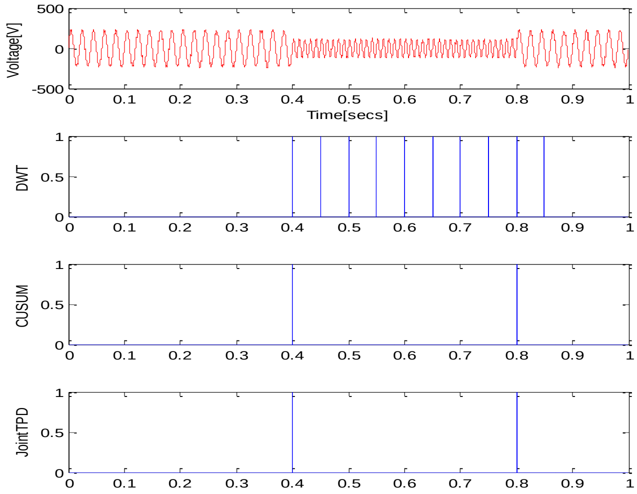


Fig. 9: Comparison of DWT, CUSUM and JTPD for voltage dip event in synthetic signal waveform

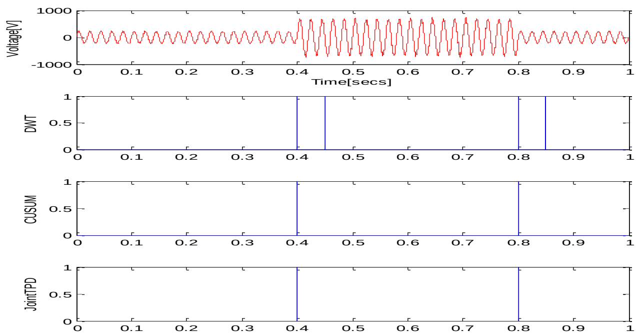


Fig. 10: Comparison of DWT, CUSUM and JTPD for voltage swell event in synthetic signal waveform.

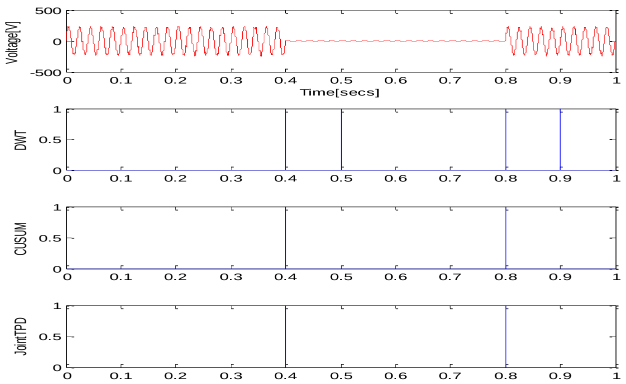


Fig. 11: Comparison of DWT, CUSUM and JTPD for voltage interruption event in synthetic signal waveform.

4 Conclusion

The power quality events of interest in this research are voltage swell, voltage dip and voltage interruption. The detection rate of CUSUM TPD scheme, DWT TPD scheme and a developed JTPD scheme has been investigated. The developed JTPD scheme for PQ detection ranks with the output of the CUSUM and the DWT schemes using a modified least square (MLS) operator to give more accurate triggering point detection. The PQ event detection schemes were applied to generated synthetic voltage signal waveforms containing the PQ events.

The performance of the CUSUM, DWT and JTPD schemes in terms of the detection error of detecting triggering points of the PQ events in synthetic signal waveforms reveals that the developed JTPD is the most accurate as it gives relatively the least error values; this is followed by the CUSUM which gives better accuracy compared to the DWT scheme judging by the lower error values obtained with the CUSUM.

Future work can use real-time signal waveforms as against synthetic signal waveforms used to verify the detection rate of JTPD as applied to power quality events. Also, other PQ events could as well be used rather those used in this research.

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