平衡三相非弦波負載之新型功率因數偵測器

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摘要

本論文旨在發展適用於三相非弦波負載電流之新型功率因數偵測器。由於充份應用三相平衡系統之特性，因此，使用於三相弦波系統時，具有瞬時暫態響應之能力，沒有任何時間延遲；而且，所提出之偵測器改善傳統技術，僅能適用於弦波信號之缺點，即本文之方法不僅可適用於弦波信號亦可適用於非弦波信號。並且，所提出之偵測器具有極佳之穩態特性。詳細之理論分析、硬體製作及實驗結果均於文中詳加說明，以驗証本文所提方法之可行性。

關鍵詞：功率因數偵測器，非弦波負載電流

A novel power factor detector for balanced three-phase non-sinusoidal loads

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Abstract

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I. Introduction

The power factor is an important characteristic in research on power quality. Recently, there has been extensive use of non-linear loads such as ac and dc servomotors, rectifier sets and electric arc furnaces, all contribute to the pollution in a power system, severely degrading the power quality. Therefore, rapid and accurate measurement of the correct power factor of current with large harmonic components is an important topic in the study of the power quality. Some systems require a power factor detector with a fast response characteristic to improve their transient performance. For example, power factor detectors can be used in control loops of power system, or in active power filters [1-2].

Many techniques have been developed to measure the power factor of the electronic circuits and power systems. The traditional Ferraris type power factor meters have the disadvantages of being large and heavy with slow transient response. Thus, they are not suitable for use in many systems which require rapid transient response [1-2].

In recent years, digital and analog power factor detectors have been developed. Although, they are inexpensive, their complicated circuit configuration together with the low-pass filters or integrators used in several circuit structure necessary to realize the averaged signal function [3-4], limit their use in instantaneous power factor measurement. The transient response of traditional detectors has been improved [5-7], but these detectors can not achieve instantaneous response when used in the three-phase linear loads, and also they can not accurately measure a system with non-sinusoidal load currents.

In this paper, a novel power factor detector for balanced three-phase non-sinusoidal load currents is proposed. The proposed power factor detector can achieve instantaneous response for balanced three-phase linear loads. In addition, the proposed detector possesses the following advantages:

(a) Compared with the existing detectors no any low-pass filters or integrators are used in this new detector.

(b) It is applicable for systems with load current having large harmonic components.

(c) This detector possesses an excellent accuracy up to full scale.

(d) There is a larger range of detectable power factor angle, from 0° to 180°.

(e) The proposed detector is independent of phase sequence.

II. Definition of power factor

Source voltage and load current signals can be expressed by Fourier series, i.e.

$$v_S(t) = \sum_{n=1}^{\infty} \sqrt{2} V_n \sin(n\omega t + \alpha_n)\,, \tag{1}$$

$$i_L(t) = \sum_{n=1}^{\infty} \sqrt{2} I_n \sin(n\omega t + \beta_n)\,, \tag{2}$$

where, dc component in $v_S(t)$ and $i_L(t)$ has been assumed to be zero.

The definition of real power is the average of the instantaneous product of voltage $v_S(t)$ and current $i_L(t)$, that is,

$$P = \frac{1}{T}\int_0^T v_S(t)\, i_L(t)\, dt\,, \tag{3}$$

where, T is the period of $v_S(t)$.

Substitution of equations (1) and (2) into equation (3) yields the following result:

$$\begin{aligned} P &= \sum_{n=1}^{\infty} V_n I_n \cos(\alpha_n - \beta_n) \\ &= \sum_{n=1}^{\infty} V_n I_n \cos(\theta_n) \end{aligned} \tag{4}$$

where, θ_n is the phase angle difference between the nth order harmonic component of $v_S(t)$ and $i_L(t)$.

Apparent power definition as the total volt-amperes value, i.e. the product of the rms value of voltage and current,

$$S = V_{rms} I_{rms} = \sqrt{\sum_{n=1}^{\infty} V_n^2} \sqrt{\sum_{n=1}^{\infty} I_n^2} \tag{5}$$

where, V_{rms} is the rms value of $v_S(t)$ and I_{rms} is the rms value of $i_L(t)$.

The definition of power factor is the ratio of real power (P) over apparent power (S),

$$\begin{aligned} PF &\equiv \frac{P}{S} \\ &\equiv \frac{\frac{1}{T}\int_0^T v_S(t)\, i_L(t)\, dt}{V_{rms} I_{rms}} \\ &\equiv \frac{\sum_{n=1}^{\infty} V_n I_n \cos(\theta_n)}{\sqrt{\sum_{n=1}^{\infty} V_n^2} \sqrt{\sum_{n=1}^{\infty} I_n^2}} \end{aligned} \tag{6}$$

A. Balanced three-phase linear load condition

Assuming both source voltages and load currents as balanced three-phase sine waves, i.e. balanced three-phase linear load condition, then phase voltage and current can be expressed as,

$$v_S(t) = \sqrt{2} V_1 \sin(\omega t + \alpha_1) \tag{7}$$

$$i_L(t) = \sqrt{2} I_1 \sin(\omega t + \beta_1) \tag{8}$$

Substitution of equations (7) and (8) into equation (6) yields the following result:

$$PF = \frac{V_1 I_1 \cos\theta_1}{V_1 I_1} = \cos\theta_1 \tag{9}$$

where, θ_1 is the phase angle difference between α_1 and β_1.

Evidently, the power factor is independent of the amplitude of $v_S(t)$ and $i_L(t)$, but it is dependent on the phase angle between $v_S(t)$ and $i_L(t)$ in cosine.

B. Balanced three-phase nonlinear load condition

If the source voltages are balanced three-phase sine waves and the load currents are balanced three-phase non-sinusoidal waves, i.e. balanced three-phase nonlinear load condition, then phase voltage and current can be expressed as,

$$v_S(t) = \sqrt{2} V_1 \sin(\omega t + \alpha_1) \tag{10}$$

$$i_L(t) = \sum_{n=1}^{\infty} \sqrt{2} I_n \sin(n\omega t + \beta_n) \tag{11}$$

and,

$$\begin{aligned} PF &= \frac{V_1 I_1 \cos\theta_1}{V_1 I_{rms}} \\ &= \frac{I_1}{I_{rms}} \cos\theta_1 \end{aligned} \tag{12}$$

One can see from equation (12) that, if the load current is balanced three-phase sine waves i.e. $I_{rms}=I_1$, the result is identical to equation (9). Therefore, it is clear that equation (12) can be used not only for non-linear loads, but also for linear loads.

III. Principle of Operation

Assume the input three-phase voltage as

$$v_a(t) = V_m \sin(\omega t), \tag{13}$$

$$v_b(t) = V_m \sin(\omega t - 120°), \tag{14}$$

$$v_c(t) = V_m \sin(\omega t + 120°), \tag{15}$$

where,

V_m: peak voltage,

ω: angular frequency.

First, feed the three-phase ac input voltages $v_a(t)$, $v_b(t)$ and $v_c(t)$ through a reference sine wave generator, producing reference voltages $v_{ar}(t)$, $v_{br}(t)$ and $v_{cr}(t)$ respectively. The peak value of three voltages is unity amplitude (i.e. 1V), and respectively same phase with $v_a(t)$, $v_b(t)$ and $v_c(t)$, therefore,

$$v_{ar}(t) = \sin(\omega t) \tag{16}$$

$$v_{br}(t) = \sin(\omega t - 120°) \tag{17}$$

$$v_{cr}(t) = \sin(\omega t + 120°) \tag{18}$$

Alternatively, if three-phase load currents $i_{La}(t)$, $i_{Lb}(t)$ and $i_{Lc}(t)$ contain large amounts of harmonic components, then a band-pass filter is used to eliminate the harmonic components and only the fundamental component of the three wave pass through. Then one can obtain,

$$i_{La1}(t) = \sqrt{2} I_1 \sin(\omega t - \theta_1) \tag{19}$$

$$i_{Lb1}(t) = \sqrt{2} I_1 \sin(\omega t - \theta_1 - 120°) \tag{20}$$

$$i_{Lc1}(t) = \sqrt{2} I_1 \sin(\omega t - \theta_1 + 120°) \tag{21}$$

Multiplying $v_{ar}(t)$ by $i_{La1}(t)$, $v_{br}(t)$ by $i_{Lb1}(t)$ and $v_{cr}(t)$ by $i_{Lc1}(t)$, and summing up the product, gives,

$$\begin{aligned} v_{o1}(t) &= v_{ar}(t) i_{La1}(t) + v_{br}(t) i_{Lb1}(t) + v_{cr}(t) i_{Lc1}(t) \\ &= \frac{3}{\sqrt{2}} K I_1 \cos\theta_1 \end{aligned} \tag{22}$$

where K is the scaling factor of the multiplier. From equation (22), it can be seen that $v_{01}(t)$ is the numerator portion of the PF definition in equation (12). Furthermore, the denominator portion of PF definition in equation (12) is the rms value of the load current. When the load current is balanced in three-phase, any phase load current can be used for passing through an rms-to-dc converter, one can get,

$$v_{o2}(t) = I_{rms} \tag{23}$$

and then passing the $v_{01}(t)$ and $v_{02}(t)$ through a divider, yields,

$$v_o(t) = \frac{v_{o1}(t)}{v_{o2}(t)} = \frac{3KK_1 I_1 \cos\theta_1}{\sqrt{2}\, I_{rms}} \tag{24}$$

where K_1 is the scaling factor of the divider. From the above equation, one can see the output voltage $v_0(t)$ is the power factor value of source voltage and load current after appropriate adjustment of the scaling factor of multiplier and divider. Fig. 1 shows the block diagram of the basic principle of the proposed detector.

IV. Hardware Implementation

The prototype hardware circuit of the three-phase power factor detector is implemented as shown in Fig. 2 in order to avoid the measurement error resulting from voltage fluctuation in the three-phase source. Thus, the voltage signal $v_a(t)$, $v_b(t)$ and $v_c(t)$ of the three-phase source passes through the reference sine wave generation circuit to produce a three-phase sine wave reference signal which has the same phase as $v_a(t)$, $v_b(t)$ and $v_c(t)$ but the peak voltage constantly at unity amplitude (i.e. 1V). Therefore, a sine wave generation circuit is used to generate the reference signal required for calculation. In addition, the reference sine wave generation circuits make the output independent of the input voltage fluctuation. The reference sine wave generation circuit is composed of a comparator, 60*Hz* band pass filter and scale amplifier, and its output is sent to the pin *X1* of each multiplier (AD 534).

On the other hand, the load currents $i_{La}(t)$, $i_{Lb}(t)$ and $i_{Lc}(t)$ are fed into an inverting amplifier and 60*Hz* band pass filter to obtain the fundamental components of the three-phase load currents, and the fundamental components of the load currents are connected to the pin Y1 of each multiplier (AD 534). Finally, the output of the three sets multipliers are added together and the scaling factors are properly selected. Hence, one can get the product of rms value of the fundamental components of the load current, I_1, and the displacement power factor, $\cos\theta_1$. Then, one can obtain a dc voltage to represent $I_1\cos\theta_1$. Alternatively, any phase load current in balanced three-phase system can be fed into an rms-to-dc converter (AD 536), to obtain the rms value I_{rms} of the non-linear load current. Finally, the $I_1\cos\theta_1$ and I_{rms} are connected to pin Z2 and X1 of a divider (AD 534), respectively, in order to obtain a dc output voltage, $v_o(t)$ representing the power factor between the input source voltages and load currents.

V. Experimental results

In order to confirm the feasibility and performance of the proposed power factor detector, a prototype was constructed as shown in Fig. 2, where the most commonly used operation amplifier (LM 741), the analogue multiplier and divider (AD 534), and the rms-to-dc converter (AD 536) are used. The output power factor is amplified tenfold in scale to facilitate the observation of output results.

A. Steady-state performance

For the source voltage $v_s(t)$ and the load current $i_L(t)$ shown in Figs. 3(a) and (b), the $v_s(t)$ and $i_L(t)$ are both sine wave and differ by 45° in phase. From Fig. 3(c), it can be observed that the output power factor value is extremely close to its ideal value of 7.07V. Secondly, Figs. 4(a) and (b) indicate that the source voltage $v_s(t)$ and the load current $i_L(t)$ are also both sine wave, with the phase difference of the waveforms being 90°. Fig. 4(c) shows that its power factor value is extremely close to its ideal value of 0V. From the above results, it is apparent that the proposed power factor detector can accurately measure the power factor in linear load.

In addition, to confirm whether the proposed power factor detector can accurately measure the power factor in non-linear load or not, a load current signal with a large amount of 3rd order harmonic components is used as shown in Fig. 5(b). Fig. 5(c) indicates the waveform of load current signal passing the band-passed filter, clearly shows that only the fundamental component passed. Fig. 5(d) shows the obtained power factor value as –5.87V.

Fig. 6 shows a typical result of the input-to-output characteristic of the proposed power factor detector. The source frequency is 60 Hz, and the phase difference between the source voltage $v_s(t)$ and the load current $i_L(t)$ is varied from 0° up to the full scale of 180°. The solid line represents the theoretical results, and the star points are the measured results. From Fig. 6 it can be seen that the error between the theoretical and experimental value is not very significant. The error sources are mainly due to the limited accuracy of the analogue multiplier and the divider (AD 534), and the rms-to-dc converter (AD 536), as well as the nonzero offset voltage of the operation amplifier. From the above results, it is seen that the proposed power factor detector can indeed measure the power factor in linear and/or nonlinear loads.

B. Transient response

It is known that the settling time of conventional power factor detectors implemented by second-order Butterworth low-pass filters may last up to 20 ms. The proposed detector is able to achieve an almost instantaneous response for balanced three-phase sinusoidal load currents. Figs. 7~9 indicate some transient responses for different step power factor angle changes, namely $60^{o}\rightarrow 120^{o}\rightarrow 160^{o}$, $135^{o}\rightarrow 45^{o}\rightarrow 135^{o}$, and $150^{o}\rightarrow 30^{o}\rightarrow 150^{o}$, respectively. From Figs. 7~9, it can be observed that the proposed detector can achieve almost instantaneous response. Hence, its transient response is superior to the conventional detectors.

VI. Conclusions

In this paper, a fast power factor detector for three-phase non-sinusoidal load currents is proposed. The proposed detector improves the drawback of the conventional detectors that can only measure the power factor of linear loads. This novel detector is able to achieve an instantaneous response for balanced three-phase linear loads. Therefore, its transient response is superior to the conventional detectors. Because of its promising accuracy and excellent transient response performance, it can be used to improve the system transient performance in many systems such as the control of power systems, active power filters, etc.

VII. References

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Figure captions

Figure 1 Basic principle of the proposed three-phase power factor detector.

Figure 2 Circuit diagram of the prototype detector.

Figure 3 Steady-state experimental results for the proposed detector where the source voltage $v_a(t)$ and load current $i_{La}(t)$ are both pure sine wave, differing 45° in phase.

Figure 4 Steady-state experimental results for the proposed detector where the source voltage $v_a(t)$ and load current $i_{La}(t)$ are both pure sine wave, differing 90° in phase.

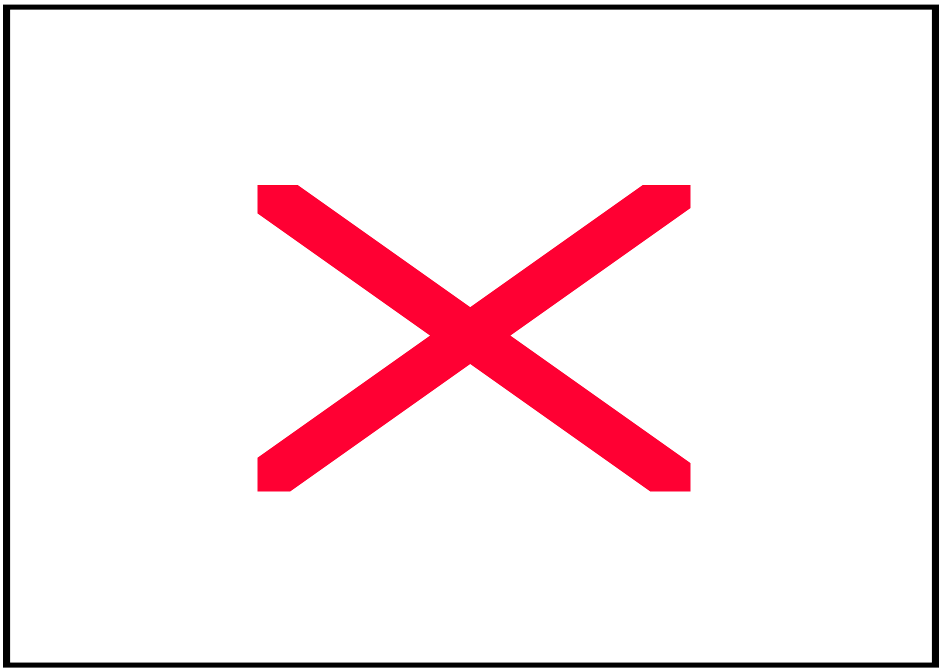
Figure 5 Steady-state experimental results for the proposed detector where the source voltage $v_a(t)$ is pure sine wave and load current $i_{La}(t)$ with a large amount of 3rd order harmonic components.

Figure 6 Input-to-output characteristic of the proposed power factor detector.

Figure 7 Transient response of the proposed detector for step power factor angle change from 60º→120º→60º.

Figure 8 Transient response of the proposed detector for step power factor angle change from 135º→45º→135º.

Figure 9 Transient response of the proposed detector for step power factor angle change from 150º→30º→150º.



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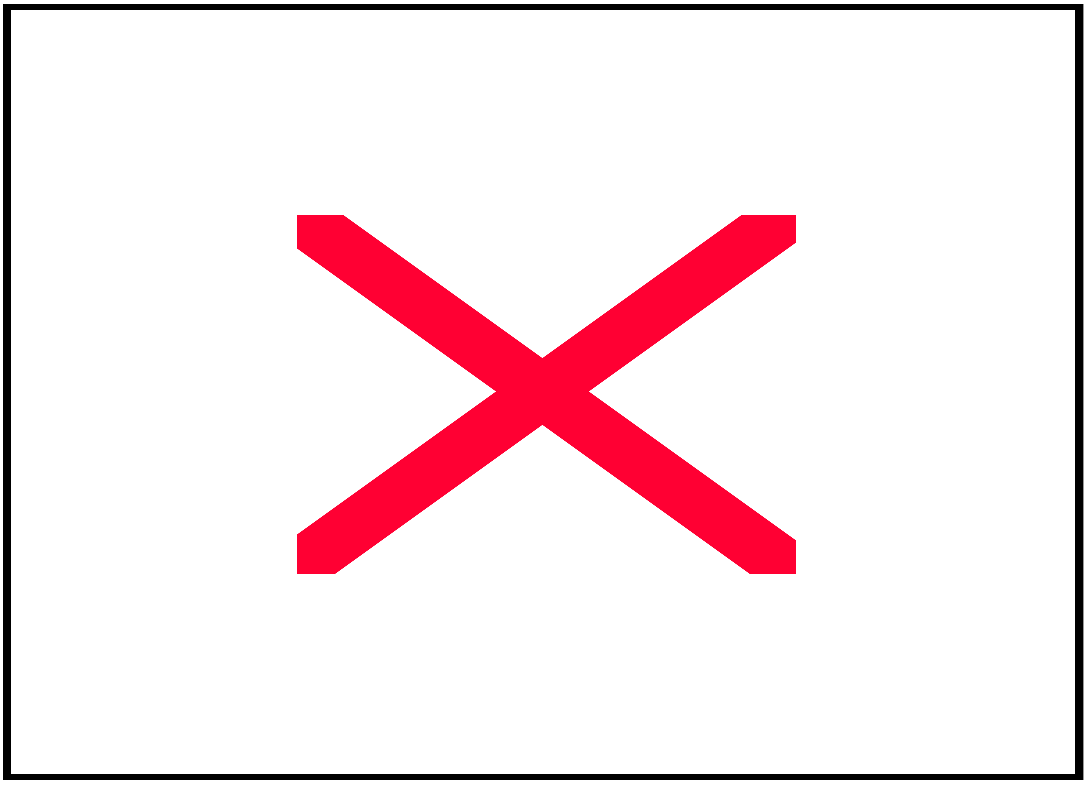


Figure 2 Circuit diagram of the prototype detector.

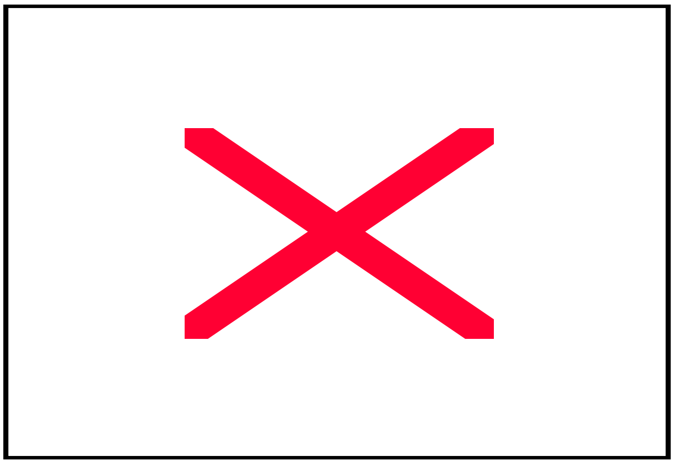


Figure 3 Steady-state experimental results for the proposed detector where the source voltage $v_a(t)$ and load current $i_{La}(t)$ are both pure sine wave, differing 45° in phase.

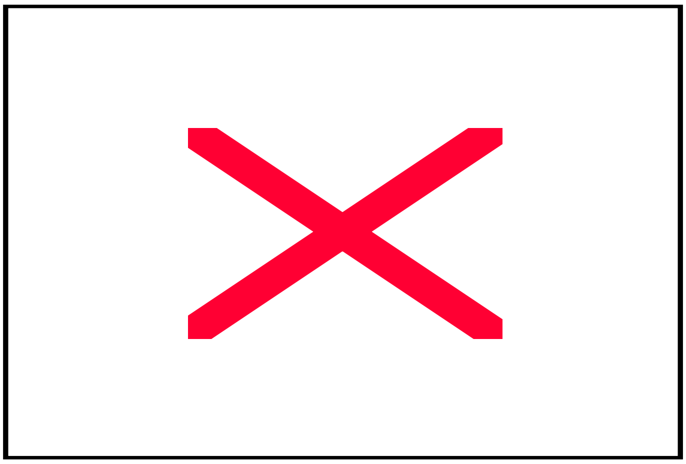


Figure 4 Steady-state experimental results for the proposed detector where the source voltage $v_a(t)$ and load current $i_{La}(t)$ are both pure sine wave, differing 90° in phase.

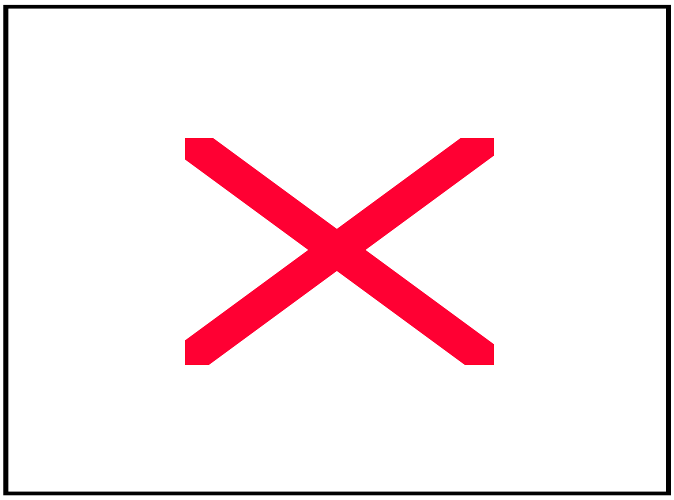


Figure 5 Steady-state experimental results for the proposed detector where the source voltage $v_a(t)$ is pure sine wave and load current $i_{La}(t)$ with a large amount of 3^{rd} order harmonic components.

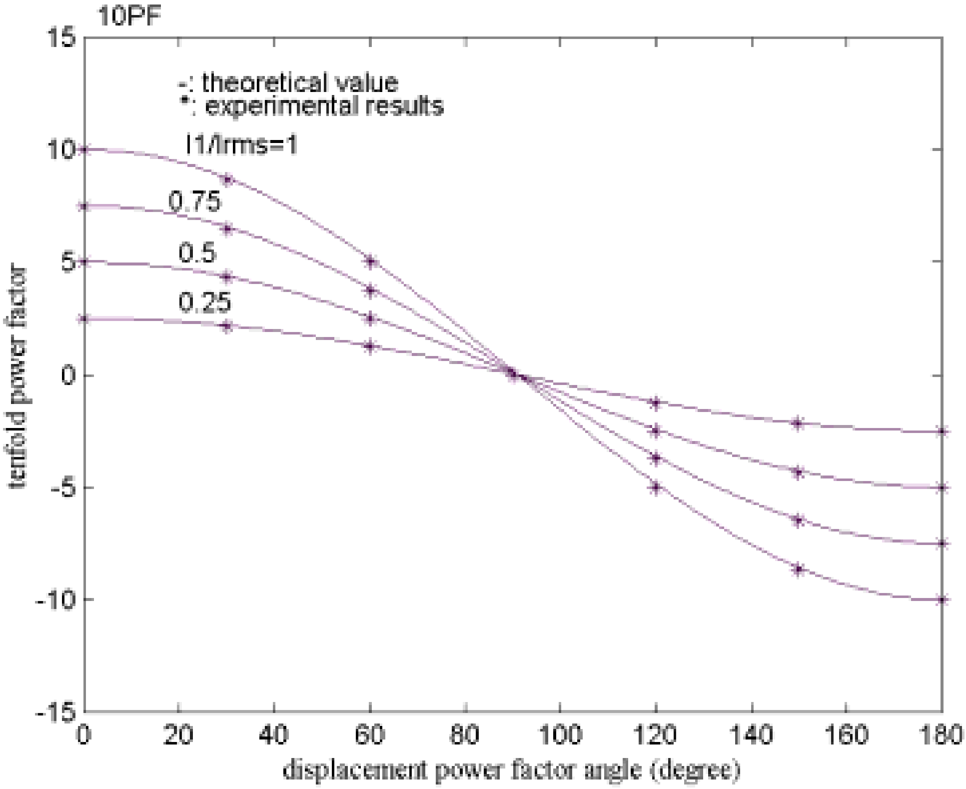


Figure 6 Input-to-output characteristic of the proposed power factor detector.

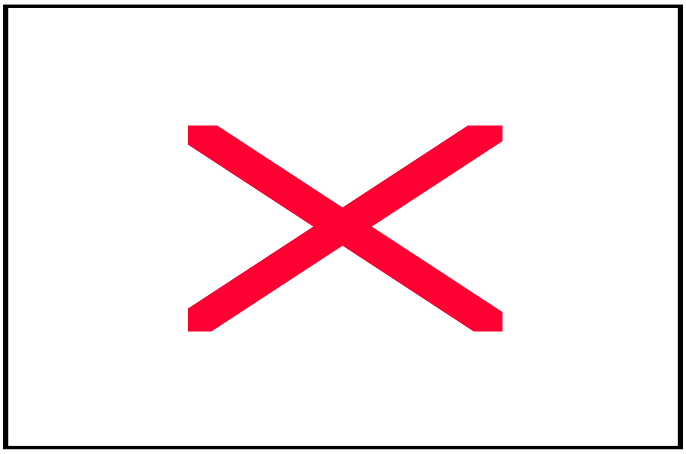


Figure 7 Transient response of the proposed detector for step power factor angle change from 60º→120º→60º.

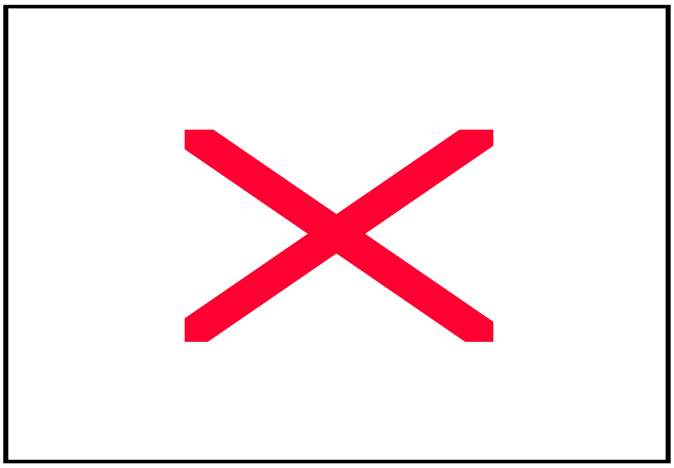
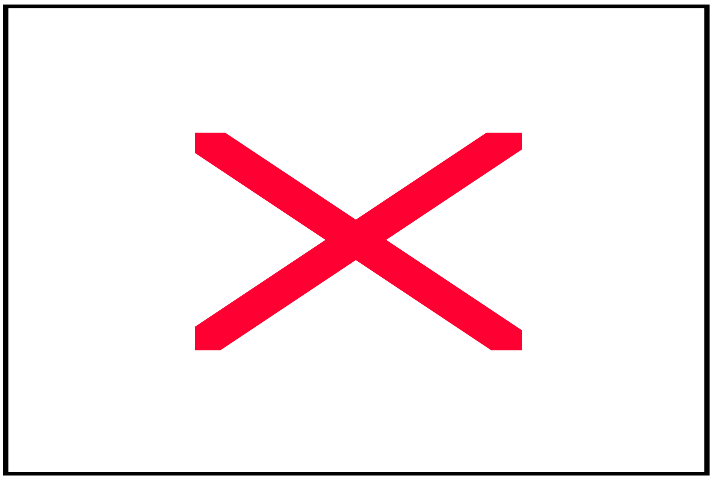


Figure 8 Transient response of the proposed detector for step power factor angle change from 135º→45º→135º.



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