Design of Digital Phase-locking Amplifier Applied in Detection of Weak Photoelectric Signals

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Abstract. Phase-locking amplifier technology belongs to one of significant branches in scientific research field of detection of weak photoelectric signals and also one of important and effective methods of detecting weak signals. Digital phase-locking amplifiers available now usually are realized based on DSP or PC system, its relevant operations on digits belong to software algorithm essentially and complicated in algorithm, which have higher requirements on microprocessor. Therefore, this thesis has put forward a new method of design of digital phase-locking amplifier based on circuit structure relevant to digits in new type, simulation on Matlab software in demodulation algorithm relevant to digits.

Introduction

Phase-locking amplifier technology belongs to one of significant branches in scientific research field of detection of weak photoelectric signals and also one of important methods of testing weak signals. It involves precision measurement of weak signals in many researches and application areas at present. However, noises must exist for any system, when the signals measured are weak, how to draw out useful signals submerged in strong noise background has become a focus in scientific research.

Principals and methods of weak signals test technology

Operational principal of phase-locking amplifier belongs to one of the important methods of weak signal detection theory, therefore, research on operational principal of phase-locking amplifier requires research on weak signal detection theory first.

When the signals measured are so weak and easy to submerge in noises, it is difficult to test them. Weak signal detection is a newly emerged technical subject which draws out useful signals from noises with electronics and signal treatment method in modern times.

In recent decades, there have been many researches on statistical characteristics of signals and noises. It provides theoretical foundation for detection of weak signals submerged in noises background. And put forward many detection methods of signals submerged in noise background according to different characteristics of noises and signals. Meanwhile, development of electric information technology creates material conditions for realization of these methods.

Traditional detection method of weak signals has specifications in detail in works of detection of weak signals and we will not repeat here, we will only make brief introduction on two new theoretical methods introduced in detection of weak signals in recent years.

Weak signal detection based on chaos theory. Duffing equation is nonlinear vibrating system which has nonlinear resilience, under periodic external force, Duffing equation is:

$$\ddot{x} + a\dot{x} + kx + \mu x^3 = F\cos\omega t \qquad (1)$$

In the equation, a represents camping coefficient, k represents linear resilience coefficient, μ represents nonlinear resilience coefficient, F and ω are amplitude and frequency respectively of periodic external force, $F\cos\omega t$ represents periodic external force. When k=-1, μ=1, the equation changed into

$$\ddot{x} + a\dot{x} - x + x^3 = F\cos\omega t \qquad (2)$$

Suppose that besides periodic external force amplitude F is the variable, the rest are constants, that is, F is the bifurcation parameter. The actions of the system change regularly with the change of parameter F.

When there are subtle changes occur near certain deterministic value of parameter of chaotic oscillator, the chaotic oscillator will produce obvious phase change phenomena, changing from chaos state to periodic state or from periodic state to chaos state. Regarding signal measured as perturbation of periodic force parameter and incorporate into the corresponding system of Diffing oscillator formula (2). Suppose that the form of the signal to be detected is

$$f\cos(\omega t + \beta) + n(t)\,. \qquad (3)$$

In the equation, f represents the amplitude of characteristic signal, ω represents frequency of characteristic signal, β represents initial phase of characteristic signal, n(t) represents noises. Adjusting parameters in formula (3) to make amplitude of external force F on the verge of obvious change of system state, that is, near the bifurcation, influence of noises on change of system state at this time is so little while characteristic signal $f\cos(\omega t + \beta)$ measured plays a key role in change of system state. For convenience of application, incorporating signal to be measured to rewrite the vibrator formula (2) of Dumng as: $\dot{x} = y$

$$\dot{y} = -ay + x - x^3 + F\cos\omega t + f\cos(\omega t + \beta) + n(t) \qquad (4)$$

In application, phase change of system state from chaos state to periodic state shall be selected as the evidence of judgment. When there is weak characteristic signal $f\cos(\omega t + \beta)$ in the signal to be measured, the system is disturbed, change of Duffing vibrator on phase diagram is obvious even under big noise. Through recognizing whether the system is in chaos state or periodic state in large size, we could further judge whether there is weak characteristic signal appeared in the signal detected [19].

Weak signal detection based on analysis of wavelet transform. Wavelet is a family of functions produced by translation and stretch of generating function of wavelet ψ(x):

$$\psi_{ab}(x) = |a|^{-1/2}\,\psi(\frac{x-b}{a}) \qquad (5)$$

In which a represents scale factor and b represents shift factor.

Wavelet transform (CWT)of successive signal $F(x) \in L^2(x)$ is

$$W_{ab}(a,b) = < f, \psi_{ab} > = |a|^{-1/2} \int f(x)\overline{\psi(\frac{x-b}{a})}dx \qquad (6)$$

In practical application, $a = 2^j$ and $b = k2^j$ to conduct discretization to obtain progression of wavelet:

$$f(x) = \sum_{j\in z}\sum_{k\in z} f, \psi_{j,k} > \bar{\psi}_{j,k}(x) \qquad (7)$$

$$c_{j,k} = < f, \psi_{j,k} > = \int f(x)\overline{\psi_{j,k}(x)}dx$$

In which $\psi_{j,k}(x) = 2^{-j/2}\psi(2^{-j}t - k)$ (8)

The wavelet transform likes band pass filter under various scales, setting certain scale m0 as the scope, band pass filter unit in different frequencies corresponding to various under m0 as similarity of detailed characteristics and used to draw out basic characteristics above m0 .

Operational principal of measuring weak square signal with phase-locking amplifier in digital orthogonal vector type

Phase-locking amplifier in orthogonal vector type is also referred to as dual phase-locking amplifier, that is, adopt two identical signal paths and correlators spurred by two symmetrical square waves in orthogonality(difference between phase positions is 90O) its outputs of two

correlators are shown in same-phase output I and perpendicular output Q, then I= R_{sy} and Q= R_{sy} according to previous analysis, we could obtain expression of polar coordinates with vector transform circuit from right angle axes to polar coordinates:

$$A=\begin{cases}\dfrac{R_{sy}+R_{sy'}}{B}, & 0<\theta\le\pi/2\\[2ex] \dfrac{B}{R_{sy'}-R_{sy}}, & \pi/2<\theta\le\pi\end{cases} \tag{9}$$

$$\theta=\begin{cases}\dfrac{\pi R_{sy'}}{2(R_{sy}+R_{sy'})}, & 0<\theta\le\pi/2\\[2ex] \dfrac{2\pi R_{sy}-\pi R_{sy'}}{2R_{sy}-2R_{sy'}}, & \pi/2<\theta\le\pi\end{cases} \tag{10}$$

Working process for measurement of amplifier in digital orthogonal vector type is: first of all, conducting respective sampling of signal to be detected s(t) and reference signals y(t) and y′ (t) and then conducting ADC,we could obtain discrete digital signals s(n), y(n) as well as y′ (n), corresponding operation processes are shown respectively as:

$$R_{sy}(0)=\frac{1}{2\pi}\frac{2\pi}{N}\sum_{n=0}^{N-1}s(n)y(n) \qquad \mathrm{NT_{1=}mT} \qquad \text{(both N and m are integers)} \tag{11}$$

$$R_{sy'}(0)=\frac{1}{2\pi}\frac{2\pi}{N}\sum_{n=0}^{N-1}s(n)y'(n) \qquad \mathrm{NT_{1=}mT} \qquad \text{(both N and m are integers)} \tag{12}$$

In equations (11) and (12), N represents the total points of sampling, T1 represents interval of sampling, T represents periods of signal to be detected and reference signal, due to R_{sy} and R_{sy} are same-phase output I and perpendicular output Q in phase-locking amplifier in orthogonal vector type in reality, values of I and Q could be taken into (10) and (11), that is, obtaining amplitude A and phase angle θ of square signal to be detected, which has realized vector measurement of weak square signal under polar coordinates.

Matlab simulation test and analysis

Fig. 5 is the Matlab simulation software environment.

The simulation result shows detection performances in power line interference including 50Hz and higher harmonic interference respectively of the signal to be detected. Relevant detection performances of different noises are as follows:

(1) When the interference is 50Hz power line interference and DC interference is included in square wave, oscillogram of useful signal x(t) to be detected and measurement signal s(t)including noises is shown in figure 2. Relative error of amplitude measured in test is 0.1% and relative error of phase position between 0O to 90O is 0.25%(when $\pi/2<\theta\le\pi$,the relative error of phase angles is smaller). The test also found that even if the frequency of reference signal is selected as integral multiple of 50Hz(such as 200Hz and 250Hz) the phase-locking amplifier also can detect amplitude and phase position of the weak signal x(t).

(2) Expanding the square wave of amplitude A and fundamental frequency ω into Fourier series form:

$$x(t)=\frac{4A}{\pi}\left[\cos(\omega t+\varphi)-\frac{1}{3}\cos(3\omega t+\varphi)+\frac{1}{5}\cos(5\omega t+\varphi)-\cdots\right] \tag{13}$$

Simulation test has detected performances when the interference is 3 times and 5 times of harmonic waves in formula (13), in which when the amplitude of harmonic noise is far more than

that of signal to be detected x(t), corresponding relative error of amplitude detected is 0.017% and relative error of phase position is 0.32%. Its wave form is shown in figure 3.

(3) When the interference is white noise, corresponding relative error of amplitude detected is 1% and relative error of phase position is 0.19%. Its wave form is shown in figure 4.

Figure 5 is the programming environment for Matlab software simulation and part of program.

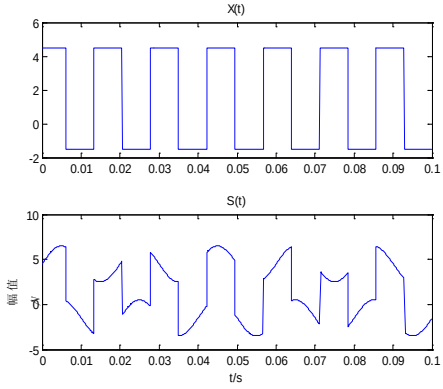

Fig. 2 signals x(t) and s(t) including power line interference

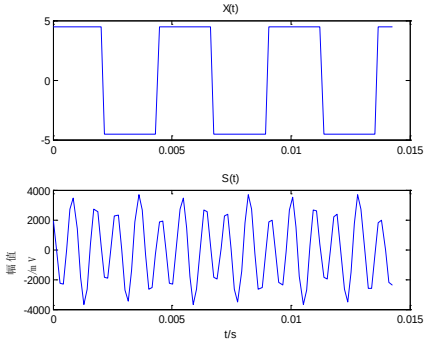

Fig. 3 signals x(t) and s(t) including higher harmonic interference

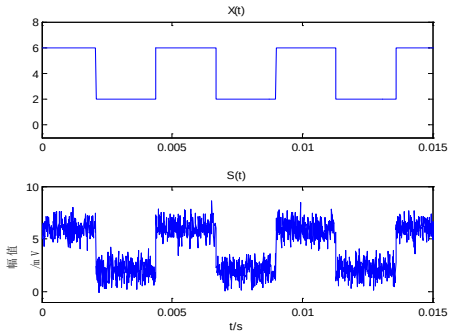

Fig. 4 signals x(t) and s(t) including white noise

Summary

We could see that this phase-locking amplifier in digital orthogonal vector type has strong restraint on higher harmonic interference and power line interference, when input noise-signal ratio is lower than 10-3 of weak signal, the detection accuracy is still high. It has certain restraint on white noise. Furthermore, this digital algorithm is easy and realization mode flexible, the digital correlator of core core elements can be realized with digital signal processor(such as DSP), field programmable gate array(FPGA) or computer software.

Due to adoption of digital design method so that avoid influences of temperature drift and noise of analogue device effectively and enhance noise-signal ratio, meanwhile this phase-locking amplifier has good capacity of resisting disturbance and measurement reproducibility.

Meanwhile, this algorithm also has some disadvantages, both data size and operand of algorithm are large adopting the above-mentioned digital digital correlator, in adopting PC, operational requirements of correlator on processor are not so obvious but obvious in adopting DSP, if reduce

adoption points and sampling period, it will affect accuracy of measurement(this problem has been verified in PC software simulation), therefore, it is necessary to conduct further optimization on this algorithm, recursion algorithm , relevant algorithm to relay type as well as polarity correlation algorithm could be adopted in optimizing algorithm.

Adopting digital design method could avoid influences of temperature drift and noise of analogue device effectively and enhance noise-signal ratio, meanwhile this phase-locking amplifier has good capacity of resisting disturbance and measurement reproducibility.

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