High Accuracy Selective Element For Electric Power Quality Indexes Measurement

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Abstract- It is necessary to carry out two selective operations for high accuracy measurement some of Electric Power Quality Indexes (EPQI): first of all it is necessary to pick up fundamental harmonic voltages from a spectrum of three phase voltage system, then, a positive, negative and zero symmetrical components. A selective devise must provide minimal amplitude and phase error in the real conditions – variation of an angular frequency of voltages. It is proposed an adaptive amplifier with spectrum conversion. The adaptive amplifier is described by non-linear differential equations with variable coefficients that may be represented by break functions. The generalized method of linearization by the describing function for static and dynamic analysis of this device is proposed. The paper illustrates the unique data of this amplifier.
Keywords: tuned amplifier, adaptive systems, multiplicative error, dynamics and static.

I. Introduction

The Electric Power Quality Indexes (EPQI) measurement is the part the main problem of electric power consumption with parallel estimation of electric power quality and elucidation culprit of change to worse this quality. The problem has many peculiarities in the case of measurement of the following static Electric Power Quality Indexes – the three phase voltage fluctuation, the asymmetry factor, the neutral point shift, the pick to pick voltage change. It is necessary to pick up fundamental harmonic components from a spectrum of three phase voltage system, pick up positive, negative and zero symmetrical components (for harmonic from 1^{st} to 40^{th} in general), provide high accuracy of voltage magnitude measurement in the case of an angular frequency instability. It is also necessary to take into account that non-informative parameter (for example, positive symmetrical sequence) may exceed in many times an informative (a negative symmetrical component). We also have to provide high resolution for measurements of phase shifts of voltage with current, of positive symmetrical component of voltage with negative and zero symmetrical components of voltages..

There are two ways for solution of this problem. The first that is grounded on the digitalization of voltages, rather expansive and is connected with low reliability, first of all, due to voltage needles that present in real three phase network and put out of action software, break big integrated circuit diodes, transistors and other elements with p-n junction.

The second way is grounded on the usage of analog elements. We usually use cascade connected a filter of symmetrical components and selective element. A filter usually consists of inductors that protect from negative influence of needles and other disturbance and therefore, provides reliability. Both cascade - connected elements should be adaptive for minimization a static and a dynamics error, caused first of all, by an angular frequency fluctuation. Analog adaptive instruments are not expansive, reliable and protected from change of environmental conditions.

A. Mechanism of acting and block diagram

Adaptive selective devises may be realized in two ways. In the first case it is possible to use a double loop adaptive tuned amplifier. One loop is used for correction a phase shift of output with input voltages by measurement this shift and use the result of measurement for control parameters of tuned amplifier of a resonance or quasi-resonance circuit. Other loop we use for minimization a multiplicative amplitude error by direct comparison of input with portion of output voltage, and use this difference for control of a controlled element, cascade connected with a tuned amplifier in the forward branch.

The second way of this problem solution is grounded on the idea of spectrum conversion. Input non-sinusoidal voltage after a tuned amplifier we convert to DC voltage. The DC voltage is converted into AC rectangular voltage by means of electronic keys. Electronic keys are controlled directly by three phase voltage system. This operation provides high accuracy of conversion. Taking into account that we have minimal gap between a real voltage (we use for control keys) and fundamental harmonic voltage, if THD less than 10%, it is used high amplitude phase voltage of three phase network for minimization of a phase shift of output with input voltage. Input and output voltages that coincide in phase than, we compare by an ordinary subtractor and use a difference after second tuned amplifier to initiate a control effort for control the gain of a tuned amplifier in the forward branch. If THD is greater than 10%, the electronic key's control may be carried out by an output voltage of the 1st tuned amplifier cascade connected a wide band amplifier. This amplifier with elimination of an output signal on the stable clipping level has negligible phase shift of input with output voltages. This permits to minimize a multiplicative error only. The block diagram (Fig.1) consists of the forward branch and the backward branch.

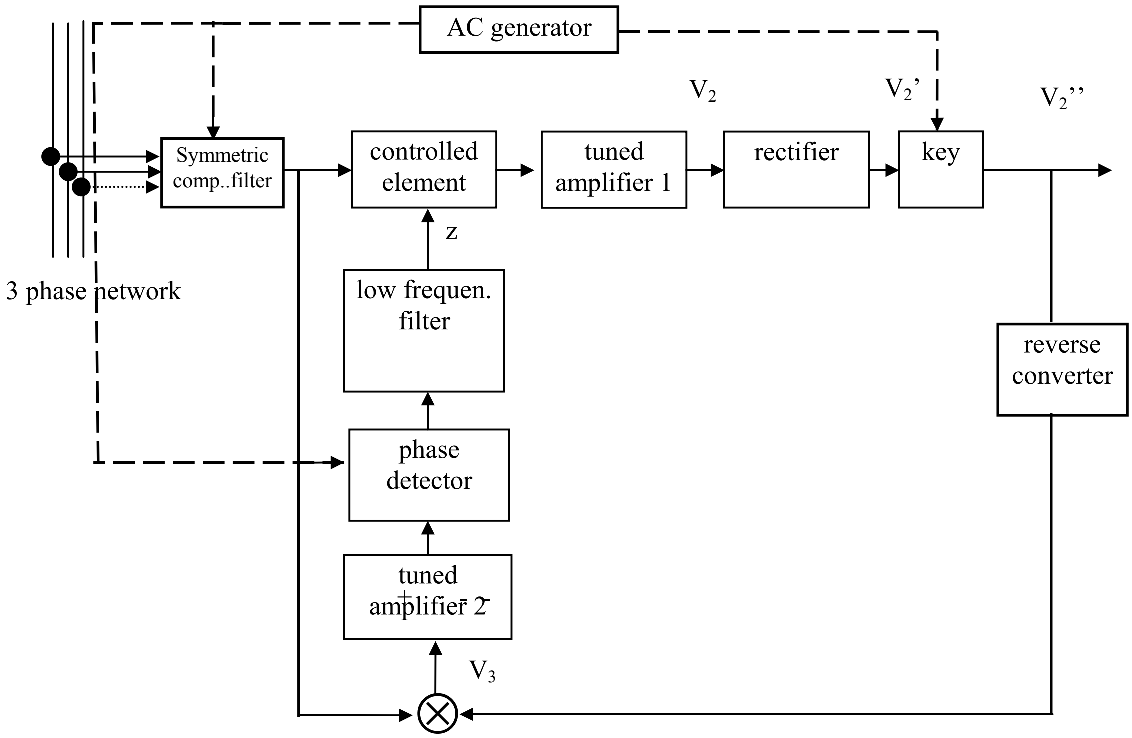

Figure 1. Block diagram of a tuned amplifier with spectrum conversion

The forward branch consists of a controlled element with controlled gain. The backward branch consists of a subtractor, second tuned amplifier and phase detector with low frequency filter. A comparator in the backward branch compares input signal (output voltage of symmetrical components filter) with rectangular voltage of AC to DC converter with stable attenuator (precise voltage divider). An attenuator transfer function in static equals to a transfer function in static of the forward branch. Therefore, in initial conditions an output voltage of the backward branch of tuned amplifier equals to zero. If a gain of the forward branch is not equal to normal, a residual output signal of second amplifier appears and is used for correction of a multiplicative error. This type of adaptive amplifiers may be considered as an element of block diagram of instruments with modulating sensors. These instruments have usually sine voltage generator that control a current (a voltage) across a sensor. An output signal of a sensor, therefore, is in phase or contr.-phase with controlling current (voltage). The general idea is grounded on the usage of the voltage of this generator for control a converter, which is used for conversion a rectified voltage of a tuned amplifier into a meander form voltage. This voltage is in phase with output signal of a sensor. The backward branch consists of a phase detector + low frequency filter or integrator. In the first case we have proportional feedback control system, in the second case latter is proportional + integral feedback control system.

B. Dynamics

A tuned amplifier with spectrum conversion consists of two resonance or quasi-resonance networks, a phase detector and a controlled element. This closed-loop control system, therefore, is described minimum by fifth order non-linear differential equation with variable coefficients. Dynamics of this type of systems may be analyzed by proposed the generalized method of linearization by the describing function.
Application of this method is grounded on the following assumptions.

1. We consider envelopes of signals instead real signals in a closed-loop system

$$V(t)\sin(\omega t+\varphi) \leftrightarrow V(t). \quad (1)$$

This assumption permits to regard such essentially non-linear elements as phase detectors or rectifier, as linear units. Moreover, this fact permits to reduce in two times the order of differential equation of resonance networks by the usage of the conception of shorten transfer functions [2].

2. A controlled element with variable parameters with a transfer function $V_2=(k'+V_3k'')V_1$ we substitute by cascade connected an adder and non-linear element that may be described by the 2nd power polynomial, for example (Fig.2):

$$V_2=k(V_1 +V_3 +a)^2\approx 2kaV_1 +2kV_1V_2,\ \text{if } k'=2ka,\ k''=2k. \quad (2)$$

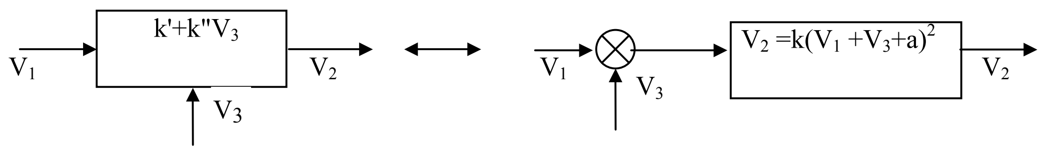

Figure. 2 Conversion of a controlled element

These assumptions permit to use the method of linearization by the describing function in classical form [1]. We suppose that the solution to a differential equation may be approximated by a Fourier series. This series we eliminate by two terms: direct component DC and 1st harmonic, taking into account that input signal is not equal to zero and a controlled element transfer function is not symmetrical to the origin of coordinate. Let's use the method of linearization for dynamics analysis of a tuned adaptive amplifier. The simplified structural block diagram after conversion, in accordance to these assumptions, is shown in Fig. 3.

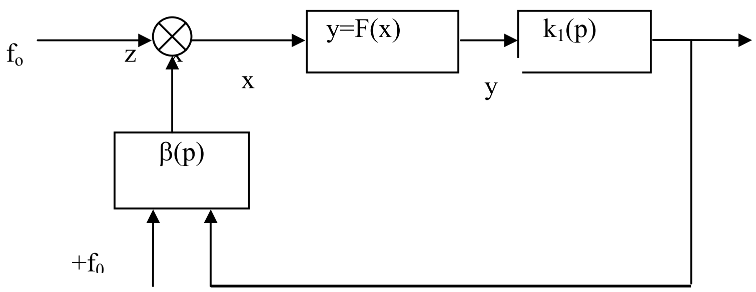

Figure 3. Simplified structural block diagram of adaptive tuned amplifier

f_o,x,y,z, - signals, $p=\sigma+j\omega$ - operator of direct Laplace transform, y=f(x) non-linear element conversion function, $k(p)k_1(p)$ –transfer function of tuned amplifier and attenuator.

First of all we determine $\mathbf{x=\varphi(f_O)}$ in result of the following equations solution

$$\mathbf{f_o,\ x_o,\ y_o,\ z_o,\ \beta(p)= \beta,\ k(p)=k.} \quad (3)$$

$$\mathbf{y_o=F(x_o),} \quad (4)$$

$$\mathbf{z_o=[f_o-k_1y_o]\beta,} \quad (4)$$

$$\mathbf{x_o=f_o+z_o,} \quad (5)$$

$$\mathbf{y_o = \frac{1}{2\pi}\int_0^{2\pi} F(x_o + A\sin\psi)d\psi} \quad (6)$$

Bold in designations means that we consider direct components of signals, or amplitude of fundamental harmonic signals

$$\mathbf{x=x_o+A_m\sin\omega t,} \quad (7)$$

$$\mathbf{y=y_o+y^*} \quad ,(8)$$

$$\mathbf{z=z_o+z^*.} \quad (9)$$

y*, z*. - first harmonics of signals, **A-** amplitude of signal.

Equations with respect to the 1st harmonic may be represented in the following form

$$x=x^*,\ y=y^*,\ z=z^*,\ y^*=q^*,\ k(p),\ \beta(p). \qquad (10)$$

A factor of linearization of the non-linear element for non-symmetrical to the origin of coordinate conversion function is:

$$q=\frac{1}{2\pi}\int_0^{2\pi} F(A\sin\psi)d\psi\ . \qquad (11)$$

Solution of algebraic equations (3)-(5) permits to determine $\mathbf{x_0}$. Then, by substitution $\mathbf{x_0}$ in (11), after simple mathematical manipulation, taking into account (7)-(10), we obtain

$$1+qk_1(p)\ \beta(p)=0. \qquad (12)$$

This is the differential equation of a closed-loop control system in operational form. For zero initial conditions $\mathbf{p}=j\omega$ and the equation (12) may be represented in the following form

$$Re(A,\omega)+ jIm(A,\omega)=1. \qquad (13)$$

The equation (13) may be represented as

$$Re(A,\omega)=0,\ \ Im(A,\omega)=1, \qquad (14)$$

and solved analytically or graphically with respect to **A**, ω.
If **A**>0 and linear part of differential equation does not satisfy to the Nyquist test, the system is non-stable for definite $\mathbf{f_0}$ and stable oscillations may exist.
If **A**<0, and linear part of differential equation satisfy to the Nyquist test, the system is stable for definite $\mathbf{f_0}$.

If ω<0, we have monotonous convergent process both for stable and usable system.
If ω> 0, we have oscillating transient.
If ω=0, we have a critical mode.
The accuracy that provides this method is low: an error may exceed 20%. This method may be recommended for preliminary analysis of stability of a system.
For synthesis of a feedback control system we must interchange a factor of linearization $q(A)\cong q_{max}$ and consider a system as a linear.

C. Static

The static analysis includes the deduction of the static equation of a close-loop system and the determination of a multiplicative error. We shall consider these problems for two cases:
1. proportional feedback control system;
2. proportional + integral feedback control system.

Proportional adaptive system

The simplified block diagram of an adaptive tuned amplifier with a controlled element is shown in Fig. 4. Taking into account that in static all derivatives are equal to zero, or, in the other words, p=0.

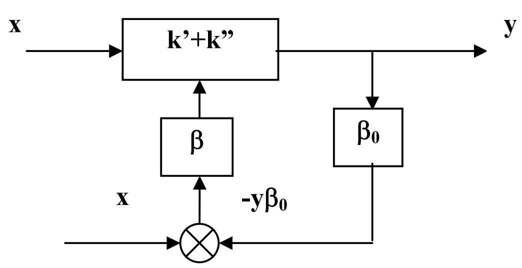

Figure 4 Simplified block diagram for static analysis

Static equations for the block-diagram Fig. 4 are following:

$$y=(k'+k''z)x, \qquad (15)$$

$$z=\beta(x-\beta_0 y). \qquad (16)$$

The solution to these algebraic equations with respect to **y** is:

$$y = \frac{k'+k''\beta x}{1+k''\beta\beta_0 x}\,x\,. \qquad (17)$$

If $\beta\to\infty$, or in the other words, if a correcting circuit gain is large, we have

$$y = \frac{k'/\beta + k''x}{1/\beta + k''\beta_0 x}\,x = \frac{x}{\beta_0} \qquad (18)$$

A multiplicative error, caused by the forward branch and the correcting circuit parameter's instability, disappears. Same result we obtain, if the forward branch gain equals to normal

$$k'=k_N=1/\beta_0, \quad y = \frac{k'+k''\beta x}{1+k''\beta\beta_0 x}\,x = x/\beta_0. \qquad (19)$$

An absolute and a relative multiplicative errors, caused by the forward branch gain change $k'\to k'+\Delta k'$ equals to

$$\Delta y = \frac{k'+\Delta k'+k''\beta x}{1+k''\beta\beta_0 x}\,x - \frac{k'+k''\beta x}{1+k''\beta\beta_0 x}\,x = \frac{\Delta k'x}{1+k''\beta\beta_0 x}, \qquad (20)$$

$$\gamma = \frac{\Delta y}{y} = \frac{\Delta k'/k'}{1+k''\beta\beta_0 x}\,. \qquad (21)$$

These formulas illustrate that an error, caused by the forward branch parameter's instability, is reduced in $1+k''\beta\beta_0 x$ times.

If we use a square detector in the correcting circuit with the square transfer function, an adaptive system's static equations are:

$$z=\beta(x^2-\beta^2_0 y^2)\approx 2\beta x(x-\beta_0 y), \qquad (22)$$
$$y=(k'+k''z)x, \qquad (23)$$

or, after simple mathematical manipulations, we obtain:

$$y = \frac{k'+2k''\beta x^2}{1+2k''\beta\beta_0 x^2}\,x. \qquad (24)$$

If $\beta\to\infty$, or $k'=k_N=1/\beta_0$, we obtain the same equation $y=x/\beta_0$.

An absolute and relative multiplicative errors are equal respectively to:

$$\Delta y = \frac{\Delta k'x}{1+2k''\beta\beta_0 x^2}, \qquad (25)$$

$$\gamma = \frac{\Delta y}{y} = \frac{\Delta k'/k'}{1+2k''\beta\beta_0 x^2}\,. \qquad (26)$$

An amplitude detector with linear characteristic is reasonable to use for a comparison of small signals (input and an output). An amplitude detector with a square characteristic should be used for comparison large signals.

Proportional and integral adaptive system

We use the same structural diagram Fig.4, and static is described by the same equations, but it is necessary to take into account that the correcting circuit consists of an integrator (one or more), and a correcting circuit's transfer function in general may be represented as

$$\mathbf{\beta(p) = \frac{(p - z_1)(p - z_2)...(p - z_m)}{p^{\nu}(p - p_1)(p - p_2)...(p - p_n)}} . \qquad (27)$$

Usually ν=1; for static **p**=0, therefore $\beta \rightarrow \infty$, $\mathbf{y = \frac{k'/\beta + k''x}{1/\beta + k''\beta_0 x} x = \frac{x}{\beta_0}}$.

A static multiplicative error is absent: this is the property of proportional + integral feedback control systems. Practically this error is small, additive and depends on the correcting circuit resolution Δ, so $\mathbf{y=(x+\Delta)*1/\beta_o}$. An error does not depend from an input and output signals magnitude.

D. Technical data

The tuned adaptive amplifier was used for development and implementation into serial production instruments for measurement electric power quality indexes

quasi-resonance frequency	50kHz
gain	300
gain with temperature	0.1 for 10^0C
gain error	0.2%
admitted variation of the main circuit's gain	20%
a settling time	0.3s.

Last parameter may be minimized by the usage of proportional + integral modification

II. Conclusions

The selective element with spectrum conversion was used in instruments for measurement positive, negative and zero symmetrical sequences of three phase voltage system and has the following data: input voltage range (with voltage divider) 5V, multiplicative error 0.2%, Q-factor 120, acceptable angular frequency fluctuation 15%.

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