A high accuracy reactive power and reactive energy meter

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Contents A high accuracy instrument for reactive power and reactive energy measurements in a single phase power network is described in the paper. The measurement principle is in accordance with IEC recommendation. Test results show that in the range of 1 to 100% of the input current the accuracy of the meter is better than 100 ppm for frequency variations of ±5% around the nominal frequency. The instrument could be used as a single-phase reactive power and reactive energy standard. A three phase version of the instrument could be used as a standard or as a revenue meter because of its high accuracy, simple design and anticipated low cost.

1 Introduction
Reactive energy is defined as a “quantity measured by a perfect watt-hour meter which carries the current of a single-phase circuit and a voltage equal in amplitude to the voltage across the single-phase circuit but in quadrature therewith” [1]. Reactive power and reactive energy measurements are generally more complex than the active power and energy measurements because additional processing of the input signals is required.

Commonly used reactive power and reactive energy measurement methods which are based on the processing of complex voltage or current differences in three-phase electrical systems assume symmetry of the phase voltages [2]. Conventional phase shifting methods, for measurements in single phase systems are sensitive to frequency variations and cause errors. As it is known from the circuit theory [3], a feasible linear circuit with time-invariant parameters cannot have phase and amplitude characteristics specified independently, i.e. the phase shift of π/2 and an amplitude both of which are independent on frequency. Therefore, a trade-off must be made which leads to numerous design possibilities. Moreover, an analysis of the various circuits [4–6] described in the literature shows that the problem of accurate phase shifting cannot be considered as satisfactorily solved.

An essentially different approach is implemented in the design of the instrument presented in this paper. In fact it is not necessary to develop an accurate and frequency-insensitive phase shifter to achieve frequency insensitive reactive power and reactive energy measurement. The frequency dependence introduced by a phase shifter could be efficiently compensated by the appropriate modification of the rest of measurement chain following the phase shifter. Consequently, instead of looking for an ideal π/2 phase shifter, the transfer function of the power conversion block is made frequency dependent in such a way that it provides the cancellation of the frequency dependence introduced by a real phase shifter. A meter for reactive power and reactive energy measurement insensitive to frequency variations based on such approach which implements a π/2 phase shift of the voltage signal and measures in accordance with the IEC [1] and IEEE [7] definition is described and its performance evaluation presented in this paper.

2 Operating principle
An integrator with the transfer function:

\[ W(j\omega) = \frac{k_i}{\omega} \cdot e^{-j\pi/2} \]

is implemented as a π/2 phase shifter of the input voltage \( u(t) \), where \( k_i \) is the integrator transfer constant. The output signal of the integrator:

\[ u^*(t) = \frac{k_i}{\omega} \cdot u \left( t - \frac{T}{4} \right) \]

where \( T \) is the input signal period, is multiplied with the input current \( i(t) \) providing a signal \( m(t) \):
\[ m(t) = k_m \cdot \frac{k_i}{\omega} \cdot u\left(t - \frac{T}{4}\right) \cdot i(t) , \tag{3} \]

where \( k_m \) is a multiplier transfer constant. The mean value \( \bar{m} \) of the multiplier output signal \( m(t) \) is defined by the equation:

\[ \bar{m} = \frac{2}{T} \int_0^{T/2} m(t) dt = \frac{k_m \cdot k_i}{\omega} \int_0^{T/2} u\left(t - \frac{T}{4}\right) \cdot i(t) dt . \tag{4} \]

To get the information about reactive power \( Q \) a multiplication of \( m(t) \) by input signal frequency \( f \) is performed as shown in Fig. 1:

\[ Q = k_M \cdot f \cdot \bar{m} . \tag{5} \]

In order to provide the measurement of reactive energy as well as reactive power with the same instrument, reactive power-to-pulse-rate conversion is implemented. A frequency-controlled analog-to-pulse-rate converter performs the transformation defined by:

\[ f_q = k_f \cdot m \cdot f , \tag{6} \]

where \( f_q \) and \( k_f \) are the output pulse rate and converter transfer constant respectively. In this way the reactive power \( Q \) is linearly transformed into the mean value \( \bar{f}_q \) of the instrument output pulse rate \( f_q \) without any dependence on the input signal frequency \( f \):

\[ \bar{f}_q = \frac{k_f \cdot k_m \cdot k_i}{2\pi} \cdot Q . \tag{7} \]

This method for reactive power and reactive energy measurements allows accurate measurements in both three phase and single phase systems regardless of the symmetry of the phase voltages or frequency variations.

3 Design of the meter

A single-phase reactive power and energy meter insensitive to frequency variations was developed [8]. An instrument for 120 V, 5 A was built in a housing of an industrial electricity meter. It is based on a high performance structure implementing an active integrator, time-division multiplier (TDM) and frequency-controlled analog-to-pulse-rate converter. The TDM, with voltage as an input to the analog-to-time-parameters converter, and the output current signal, was chosen because of its high accuracy.

Only standard components were used in the construction of the instrument. Special attention was paid to stray effects caused by imperfections in the electronic components. Junction FETs were used as analog switches because of their high speed and low charge injection. Special driver circuitry in advanced CMOS (ACL) was developed in order to get full benefit of the FETs high speed while preserving low power consumption. A single-stage current transformer was used at the current input.

A custom-designed analog-to-pulse-rate converter was developed in order to obtain the output frequency which is proportional to the product of the multiplier output \( m(t) \) and input signal frequency \( f \). Fig. 2 shows the block diagram of the converter.

The integrator, comparator, flip-flop (FF) and pulse-amplitude-modulator (PAM) form a nonlinear feedback system which operates in an oscillating mode if the input signal is nonnegative and less than one-half of the reference \( R \). In the steady-state a dynamic balance is established between the input \( m(t) \) and a feedback signal \( r(t) \) which is a train of rectangular pulses with amplitude \( R \) and duration which is equal to the period \( T_r \) of the clock signal which is connected to the flip-flop clock input (C).

Therefore, the feedback signal \( r(t) \) average value is equal to the input signal \( m(t) \) average value. Therefore, the average value \( \bar{F} \) of the oscillating frequency \( F \) is proportional to the corresponding average value \( \bar{m} \) of the input signal:

\[ \bar{F} = \frac{k}{T_r} \cdot \bar{m} \cdot \frac{R}{k} , \tag{8} \]

where \( k \) is a converter transfer constant.

A phase-locked loop is used for the frequency multiplication in order to provide for the high output frequency:

\[ f_r = N \cdot f . \tag{9} \]

Since the feedback pulses are coincident with the clock signal, the time interval between them (the instantaneous period of oscillation) is always equal to the multiple of the clock signal period \( T_r \) and is never less than \( 2T_r \). The consequence of the discrete nature of the feedback signal is that the instantaneous value of the oscillating frequency fluctuates, even when the input signal and clock frequency are constant, excluding the case when the ratio \( R/m \) is an integer, in which case the instantaneous frequency \( F \) is equal to the average frequency defined by (8). This jitter phenomenon makes the use of the feedback pulses unsuitable as the output signal of the instrument.

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Fig. 1. Simplified block diagram of the meter

Fig. 2. Frequency-controlled Non-synchronized Analog-To-Pulse-Rate Converter