Power factor measuring device using microcontroller for single-phase consumers

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Abstract. The paper presents a device with microcontroller for measuring the power factor used for single-phase low voltage electrical consumers. Voltage and current are measured, and the paper presents two constructive variants of pulse circuits (TTL compatible) used to measure the phase-shift between current and voltage. In the first constructive variant, without galvanic separation, the voltage measurement is performed with a voltage divider connected in parallel with the consumer, and the current measurement is made by a shunt resistor connected in series with the consumer. In the second construction variant, with galvanic separation, the voltage is measured by a step-down voltage transformer, and the current is measured with a current transformer that has a load resistance. The signals coming from the voltage and current measuring equipment are limited by a group of diodes, then amplified-separated, and the resulting signals are connected to the input of a XOR TTL logic gate. The signal from the XOR TTL gate output has constant amplitude pulses and time durations proportional to the phase-shift value between current and voltage. The signal after the XOR TTL gate is applied to the digital input of a microcontroller development board that, also, has an LCD shield. The program used to calculate the power factor according to the pulse length (proportional with phase-shift value) is presented. Experiments are performed with RL consumers to measure the power factor and the obtained measurements are compared with those measured with a precision device (power quality analyser).

1. Introduction

In addition to the consumption of power and active energy for the operation of electricity networks, the consumption of reactive power is the main interest, which can reach, in some situations, quite important values, especially in the case of domestic and industrial electrical loads. For the calculation of the electrical networks, it is necessary to know the reactive power consumption, respectively the value of the power factor (especially at the moments of the maximum or minimum loads of the electrical loads). Consumers with a low power factor are obliged, by natural means (e.g. the correct choice of electric machines, operating modes, etc.) or artificial (by using capacitor banks or synchronous compensators), to take measures to reduce consumption of own reactive energy [1-3].

The power factor and reactive energy compensation are closely related to the quality of electricity. A low power factor, so a high consumption of power and reactive energy, causes significant energy flows in electricity networks and, implicitly, large losses of electricity. The improvement of the power factor is a problem of a special technical-economic importance in the operation of electrical installations and is obtained by reducing the circulation of reactive power in different points of the electric power system, as close as possible to electrical loads [4-8].
At present, by using artificial method, it has become more advantageous to produce locally reactive power with specialized sources, installed in the power system and industrial consumers, than the transport of reactive energy from remote power plants. In the action of local compensation of reactive energy consumption, industrial consumers have the task of achieving a neutral power factor (for low voltage is 0.9), which depends on the voltage level. The compensation of the reactive power in the electric networks is done depending on the energy situation and the position in the system of the areas with electrical loads [2], [9-11].

In low voltage networks for balanced areas in terms of consumption and active power production, a compensation of power factor (on fundamental) is 0.9 - 0.93, at the peak of electrical loads, is generally satisfactory. For deficient areas supplied from the transmission network from distant power plants, the required level of compensation may reach a power factor (on fundamental) 0.98 - 1. The differential distribution of the level of compensation by zones is made periodically, on the basis for examining the operation of the electric transmission network of the electric power system [2], [11].

Currently, the most common low voltage electrical consumers are single-phase. Many electrical consumers have a resistive inductive (R-L) character. It is important to be able to measure the power factor on the fundamental (voltage and current) to evaluate the reactive character of the single-phase electrical loads.

Analog power factor meters (electrodynamic, ferrodynamic and induction principles) and, currently, especially digital type (based on a microcontroller board) can be used to measure the power factor [10-12].

The paper presents, through practical realization and experiments, a power factor meter (made in two constructive variants) for measuring the power factor in single-phase electrical loads.

2. Current transformer with resistance in secondary winding

When making the power factor meter, a current transformer (CT) is also used to measure the phase shift. In the following, an analysis is made regarding the choice of the current transformer and its load resistance. On the load resistance there will be a voltage drop proportional to the value of the measured current. This voltage (proportional and almost in phase with the current), together with the voltage after a low voltage transformer is used to measure the phase shift [13].

In practice, the current transformer is used to reduce the current (from tens, hundreds or thousands of amperes) to small values (up to 1A or 5A) to be measured by ordinary devices (Figure 1). It is made of a hollow core (torus type) through which passes the conductor and the main current to be measured, which usually has high values. The secondary winding is made of a large number of turns. During operation, the current transformer must not be left without load (it must be short-circuited or have a very low load resistance, eg. an ammeter) because it behaves like a step-up voltage transformer.

Figure 1. The main use of current transformer in power engineering
The current transformer (Figure 2) is a step-down current transformer and, also, a step-up voltage transformer. To make the conversion into a voltage a low value $R_s$ load resistor is used which is connected in parallel with the secondary winding. The current transformer is usually made of a torus core, the number of turns in the primary winding is $N_1$, and the number of turns in the secondary winding is $N_2$.

![Figure 2. Design of current transformer with resistance $R_s$ connected in the secondary circuit](image)

At this transformer the solenizations are equal in primary and secondary windings:

$$N_1 \cdot I_1 = N_2 \cdot I_2$$

where $I_1$ and $I_2$ are the currents passing through the two windings (primary and secondary). The transformation ratio of the current transformer is:

$$k_i = \frac{I_1}{I_2}, \quad k_i = \frac{N_2}{N_1}$$

as $N_2 >> N_1$ results $k_i >> 1$. The voltage transformation ratio of the transformer is calculated with:

$$k_u = \frac{u_1}{u_2}; \quad k_u = \frac{N_1}{N_2}$$

so, $k_u << 1$.

The $\Delta u_s$ voltage drop across the load resistor $R_s$ is:

$$\Delta u_s = R_s \cdot I_2; \quad \Delta u_s = R_s \cdot \frac{I_1}{k_i}$$

From Eq. (4) is obtained the necessary value of the $R_s$, for a certain current transformer, when the value of the voltage drop $\Delta u_s$ is imposed:

$$R_s = \frac{\Delta u_s}{I_2} \cdot \frac{N_1}{N_2}$$

The power dissipated by the load resistance $R_s$ is determined by:

$$P_d = \Delta u_s \cdot \frac{I_1}{k_i}$$

The equivalent impedance of the current transformer CT, in this case is:

$$Z_s = \sqrt{\left[R_1 + k_i^2 \cdot \left(R_2 + R_s\right)\right]^2 + \left[2 \cdot \pi \cdot f \cdot (L_1 + k_i^2 \cdot L_2)\right]^2}$$

where $R_1$ (Ω) and $R_2$ (Ω) are the resistors of the two windings of the CT, $L_1$ (H) and $L_2$ (H) their inductances, and $f$ (Hz) the frequency of the supply voltage. The inductances of the coils are:

$$L_1 = \frac{n_1^2}{\mu_m}$$

$$L_2 = \frac{n_2^2}{\mu_m}$$

where $\mu_m$ is the reluctance of the magnetic circuit:
In these relations, $\mu_0$ (H/m) is the magnetic permeability of the vacuum ($\mu_0 = 4\pi \times 10^{-7}$ H/m), $\mu_{rT}$ (-) is the relative magnetic permeability of the material of the magnetic circuit of the current transformer, $R_T$ (m) is the mean radius of the torus, and $S_T$ (m$^2$) and $r$ (m) are the cross section of the magnetic circuit, respectively the radius of this section.

The voltage drop across the equivalent impedance of the secondary current transformer $Z_{eT}$, taking into account the relations (3), (7), (11) and (12) is:

$$\Delta u_{Tc} = I_1 Z_e$$

$$\Delta u_{Tc} = I_1 \left[ R_e + \left( \frac{N_1}{N_2} \right)^2 \left( R_S + R_0 \right) \right] + \left[ \frac{2 \pi \mu_0 \mu_{rT} \cdot r^2 \cdot N_1^2}{R_T} \right]$$

In the complex, this voltage drop is calculated with:

$$\Delta u_{Tc} = I_1 \left[ R_e + \left( \frac{N_1}{N_2} \right)^2 \left( R_S + R_0 \right) \right] + j \left[ \frac{2 \pi \mu_0 \mu_{rT} \cdot r^2 \cdot N_1^2}{R_T} \right]$$

Analyzing the above, it results that the voltage drop on the load resistance $\Delta u_{Tc}$ depends especially on $R_1$ and $L_1$ of the primary winding which must have values as small as possible (a single turn can be used in primary winding), the ratio $N_2/N_1$ which must be high (of the order of dozens), of $R_2$, $R_S$ and $L_2$ of the secondary winding (if they have higher values it determines a more important voltage drop on $R_S$).

It is stated that when conducting this study it was considered that the transformer core is unsaturated. Basically, for the current transformer to operate on the unsaturated portion of the magnetization characteristic, up to high current values (higher than the starting current value) will be used transformers with high transformation ratio ($k_i$). By using an ordinary current transformer like the one shown in Fig.2 when making a power factor meter, due to the equivalent impedance of the current transformer relative to the secondary $Z_e$, errors occur in measuring phase shift (of the order of electrical degrees) and implicitly power factor, especially when measuring low value currents (order A).

3. Electric diagrams of power factor meter

In order to measure the power factor with microcontroller, operational amplifiers are used to detect the zero passing through of the voltage and current signals and to determine the phase shift between the current phase and the voltage. The phase shift measurement is made only for the fundamental between current and voltage. Operational amplifiers convert sinusoidal wave signals with different amplitudes coming from measuring equipment (can be resistive, resistive divider or current transformer and voltage transformer) into rectangular waves with an amplitude of about 4 V, which are then connected to the inputs XOR TTL gate. The XOR logic gate output will be 1 only when the inputs have different signals for reactive loads and the XOR logic gate output is 0 when the load is resistive. So, when both voltage and current phases start and end at the same time the XOR logic gate output will be 0, and when the load is inductive or capacitive the output of the XOR logic gate is 1, because there is a phase difference between voltage and current.
In order to make the numerical power factor meter, two constructive variants of electronic schemes were made (Figures 3 and 4) [14].

In the first design variant (Figure 3), without galvanic separation, the voltage measurement is performed with a voltage divider connected in parallel with the electrical load, and the current measurement is made with a shunt resistor connected in series with the load. In the second design variant (Figure 3), with galvanic separation, the voltage is measured by a step-down voltage transformer, and the current is measured with a current transformer that has a load resistance.

![Figure 3. Power factor meter without galvanic separation](image)

In the design diagram of the power factor meter using shunt resistor and resistive divider in Figure 3, there is no galvanic separation, being dangerous both for the operator and for the power factor meter components (operational amplifiers and logic gate can be easily destroyed). The voltage is measured with a resistive divider, and a small part of the supply voltage is limited in amplitude by a group of diodes connected in antiparallel. The current measurement is performed by a shunt resistor connected in series with the consumer on the neutral conductor (N). A voltage drop appears on the shunt resistance in proportion to the value of the current passing through the load. The amplitude of the voltage drop is limited by two diodes connected in antiparallel and then amplified (amplification depending on the resistance on the 10k reaction) with an operational amplifier LM 324 at the output of which a rectangular signal of the same frequency is obtained as the supply voltage. The amplitude of the voltage drop across the load resistor is limited by the group of diodes connected in antiparallel, and then amplified by the operational amplifier LM 324 (amplification that depends on the resistance on the 10k reaction). At the output of the operational amplifier a rectangular signal (voltage) of the same frequency as the frequency of the load current is obtained. The outputs of the two operational amplifiers are connected to the inputs of the XOR logic gate. At the output of the logic gate, a voltage pulse is obtained proportional to the phase shift value. The filter capacitors in this circuit are important for removing the power supply noise and for forming the voltage pulse.

In the diagram in Figure 4 a current transformer (CT) and a voltage transformer (VT) are used to measure current and voltage, the measurement being performed with galvanic separation. In the design diagram of the numeric power factor meter using voltage transformer and current transformer (Figure 4), the voltage in the secondary VT has small values, is limited in amplitude with the group of diodes connected in antiparallel and then amplified, as in Figure 3. The current transformer has a single coil in the primary circuit, and in the secondary many coils (dozens) are made. A load resistor is connected in the secondary, the current in the primary circuit of the CT causes a voltage drop proportional to the load resistor. Like the circuit in Figure 3, the voltage on the load resistor is limited in amplitude with
the group of diodes connected in antiparallel and then amplified. Voltage signals are applied to the XOR logic gate input.

Although the transformers have no polarity, in this application the winding point of the voltage transformer is very important, because if the inputs of the CT and VT windings do not match, the digital input of Arduino will read a low power factor (PF) even with pure resistive load. That is why it is important to use the winding begging correctly (Figure 4). If the consumer has an inductive reactive character, a rectangular signal (corresponding to the current) is obtained at the output of the second operational amplifier, which is following the signal (corresponding to the voltage) obtained from the output of the first operational amplifier.

![Power factor meter with galvanic separation](image)

**Figure 4.** Power factor meter with galvanic separation

![Signals](image)

**Figure 5.** Signals at the inputs (V and I) and at the output (XOR) of XOR TTL gate

The theoretically signals from the input and at the output of XOR TTL gate are presenting in Figure 5. The output of XOR TTL is connected to a digital port of microcontroller board.

In order to make a numerical power factor meter consisting of the electronic diagrams in Figures 3 and 4, the electrical diagram in Figure 6 was made which allows (by means of two switches $S_1$ and $S_2$, each with two positions, 1 and 2, and two normally-open contacts and two normally-closed contacts) use of one of the two electronic schemes (Figure 3 or Figure 4). A particularity of this scheme is that the primary current transformer and the shunt resistor (0.8 Ω) are permanently connected in series with the single-phase load. The voltage channel and current channel (that is also a voltage) are applied to the inputs of XOR TTL gate.
When switches $S_1$ and $S_2$ are in position 1, the configuration of Figure 6 is made, the voltage and current transformers being connected in the circuit. The voltage channel (voltage drop from the secondary of the voltage transformer) connects to the input of the first operational amplifier LM 324, and the current channel (voltage drop to the resistance from the secondary of the current transformer) connects to the input of the second operational amplifier LM 324. When switches $S_1$ and $S_2$ are in position 2, the configuration in Figure 3 is made, the resistive divider and the shunt resistor being connected in the circuit. The voltage channel (voltage drop in the voltage divider) is connected to the input of the first operational amplifier LM 324, and the current channel (voltage drop on the shunt resistor) is connected to the input of the second operational amplifier LM 324.

In the general case of single-phase non-sinusoidal electrical loads, the instantaneous value of the power factor can be compute with:

$$\lambda_p = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2 + D^2}} = \frac{P}{\sqrt{P^2 + I^2}}$$

where $0 \leq \lambda_p < 1$, $P$ is the active power, $Q$ is the reactive power, $D$ is the deforming power, $S$ is the apparent power, and $F$ is the fictive power.

In sinusoidal regime (ideal case with voltage and current sinusoidal) for reactive electrical loads $D = 0$, $P \neq 0$, $F = Q \neq 0$ for symmetrically charged of single-phase electrical loads on three-phase circuits, in which the values of voltages and currents on the three phases, as well as the phase shifts between the corresponding phasors are identical, the power factor $\lambda_p$ becomes:

$$\lambda_p = \cos \phi = \frac{P}{\sqrt{P^2 + Q^2}}$$

with $0 \leq \cos \phi < 1$.

4. Arduino Uno and LCD shield use for power factor meter
Arduino Uno is an open-source platform used for electronic projects. This platform consists of an electronic board containing a microcontroller and an IDE (Integrated Development Environment) software package. The IDE is used to write the programming part (code) and load the program into the electronic board or microcontroller.

The power factor is a number between 0 and 1 which is directly related to the phase difference between the zero crossing of the voltage (voltage signal) and between the zero crossing of the current (current signal) and depends on the reactive character (inductive or capacitive) of the single-phase load.
Figure 7. Arduino and LCD shield to measure and display the pulse input

Figure 8. The flowchart of the program that measure, calculate and display power factor and phase-shift
The signal after the XOR TTL logic gate is applied to the digital pin 7 (input pin) of the Arduino Uno microcontroller which measures the pulse length to determine the phase shift and then the power factor. The Arduino Uno is connected to an LCD shield so that the power factor and phase shift can be viewed (Figure 7).

The logic diagram that was made for the program is presented in Figure 8. The initialization of the LCD, the communication speed, the pins, the frequency and the variables are performed. Four pulse values are measured and the one with the highest value is chosen. First calculate the phase-shift between voltage and current, and then calculate the power factor. If phase shift is too small or too large, power factor 1 and phase shift 0 or 360 are displayed. Otherwise, the calculated values of power factor and phase shift are displayed. The information is kept for 0.5 s after which a new measurement is made.

5. Experiments with power factor meter

Both constructive types of power factor meter from Figures 3 and 4 were experimented. It was found experimentally that power factor meter in Figure 3 is very sensitive (due to direct connection at voltage 230 V, 50 Hz) and the component parts can be easily destroyed (operational amplifiers and even Arduino Uno) after a few measurements. For this reason, further experiments were performed only with power factor meter from Figure 4 (with galvanic separation).

In Figures 9-12 several experiments were performed with different number of turns for the primary winding \( N_1 \), for the secondary winding \( N_2 \) and different values of the load resistance \( R_s \). The current through primary winding was up to 3A.

A higher number of turns in the primary circuit \( N_1 \) determine the saturation of the core and a nonlinear evolution between the secondary voltage (on \( R_s \)) and the current in the primary circuit.

A higher number of turns in the secondary circuit \( N_2 \) (of the order of tens) determines a linear evolution between the secondary voltage and the current in the primary circuit, and a lower resistance \( R_s \) determines a more linear dependence between the secondary voltage (on \( R_s \)) and primary current (Figures 9-12).

In experiments, the constructive scheme of the power factor meter with galvanic separation was used (Figure 4) and a resistive-inductive load (with a fixed resistance of 49.2 Ω) was used, which determines different currents depending on the inductance value. At the nominal voltage (230 V, 50 Hz) the current values depending on the inductors used (seven types) are presented in Figure 13. Table 1 shows the inductance values used in the experiments.

Experiments with power factor meter with galvanic separation (Figure 12)

![Graphs showing experimental results](image)

**Figure 9.** a. Secondary voltage depending on primary current, \( N_1=4, N_2=20, R_s=10 \text{ Ω} \); b. Secondary voltage depending on primary current, \( N_1=3, N_2=20, R_s=10 \text{ Ω} \)

**Table 1** Inductance values (mH) used at experiments

| \( L_1 \) | \( L_2 \) | \( L_3 \) | \( L_4 \) | \( L_5 \) | \( L_6 \) | \( L_7 \) |
|---|---|---|---|---|---|---|
| 5.36 | 6.02 | 6.9 | 7.86 | 8.75 | 14.7 | 15.1 |
Figure 10. a. Secondary voltage depending on primary current, $N_1=2$, $N_2=20$, $R_s=10\ \Omega$; b. Secondary voltage depending on primary current, $N_1=1$, $N_2=20$, $R_s=10\ \Omega$

Figure 11. a. Secondary voltage depending on primary current, $N_1=1$, $N_2=20$, $R_s=1\ \Omega$; b. Secondary voltage depending on primary current, $N_1=1$, $N_2=25$, $R_s=1\ \Omega$

Figure 12. Secondary voltage depending on primary current, $N_1=1$, $N_2=30$, $R_s=1\ \Omega$

Figure 13. Current through R-L loads at nominal voltage
In Figure 14 a comparative analysis was made for the seven electrical R-L loads, how to change the power factor for the fundamental DPF (measured with the power quality analyzer CA 8334B) and the power factor measured with the power factor meter in three situations: 10 turns, 11 turns and 14 turns in secondary winding of CT. A load resistance R_s with a value of 10 Ω was used.

In Figure 15 a comparative analysis was performed for the seven electrical R-L loads, how to change the power factor for the DPF fundamental (measured with the power quality analyzer CA 8334B) and the power factor measured with the power factor meter in six situations: 9 turns, 10 turns, 11 turns, 13 turns, 15 turns and 18 turns in secondary winding of CT. A load resistance of R_s with a value of 1 Ω was used. The measurements showed that for less reactive electrical loads (loads 1, 2, 3, 4, 5) the measurements are more accurate compared to highly reactive loads (loads 6 and 7).

In order to make more accurate measurements, a current transformer with a large number of turns in the secondary winding and a low load resistance R_s must be used.

Power factor meter can only be used to measure the power factor where the currents are not strongly deforming (THDi <15%). It cannot be used to measure the power factor at switching sources because the pulse at the output of XOR TTL gate is no longer formed correctly (Figure 16, eg. two pulses can appear instead of one).

![Figure 14. PF measurement using R_s=10 Ω](image1)

![Figure 15. PF measurement using R_s=1 Ω](image2)
6. Conclusions
After experiments the following conclusions can be made:
- The current transformer is the sensitive element from power factor meter;
- The power factor meter without galvanic separation it is not suitable for practical use (the operational amplifier, the logic gates, even Arduino could be destroy quickly), even this type of power meter measure PF better (errors < 5%);
- The power factor meter with galvanic separation can measure PF with errors <15-20%, that depends strongly from design of current transformer;
- The analysed circuits for power factor meters (Figures 3 and 4) can not be used for non linear loads (eg. switched mode power supplies, power electronics, so on) with strongly deformed current because the pulse voltage after electronic circuit is not formed correctly;
- Better results will obtain using Hall transducer to measure voltage and in particular, to measure current.

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