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ANALYSIS OF MEASUREMENT ERROR IN DIRECT AND TRANSFORMER-OPERATED MEASUREMENT SYSTEMS FOR ELECTRIC ENERGY AND MAXIMUM POWER MEASUREMENT

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Abstract. *Analysis of error in measuring electric energy and maximum power within direct and half-indirect measurement system at the voltage of 0.4kV is presented in the paper. The analysis involved all the elements of the measurement system, i.e. calibration and testing of the transformer-operated and direct digital energy meters and measuring current transformers. This equipment was also used for measurements in the transformer substation aiming at error analysis at measurements made under the real conditions. The results obtained show significant negative measurement error introduced by the energy meters under overload conditions. Energy meters have lower values of both the consumed electric energy and maximum power in this operating mode, which can be interpreted as a loss.*

Key words: *Measurement error, digital energy meters, measuring current transformers*

1. INTRODUCTION

In the early XXI century, the power system of Serbia is facing numerous strategic challenges, one of the most important ones being enhancing energy efficiency of the systems for generation, transmission and distribution of electricity.

The continual increase in electricity consumption, changed consumers' structure and inhibited construction of the resources and the network caused the long-term and excessive operation of the power system. This has resulted in its inefficient operation and has led to substantial electricity losses. These losses may be due to a number of reasons, one of major factors that require analysis being the error at measuring electric energy and maximum power (maximum average fifteen-minute active power).

The systems of half-indirect of both electric energy and maximum power include measuring current transformers and transformer-operated measurement instruments for measuring active and reactive electric energy, as well as those measurement instruments

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for electric energy and maximum power measurement in direct systems. The measuring instruments need to provide the required accuracy in operation.

Given that measuring current transformers need to meet the given accuracy class (up to 120% of the given current), the question is whether or not the measuring current transformers exceed the rated accuracy class limits when the primary current is near zero, as well as when it exceeds 120% of the rated current, and even when the overload amounts to 100%, [1, 2].

Similarly, the question is also raised as to the extent to which changes in the load at the secondary windings of measuring current transformers affect measurement accuracy. This primarily refers to replacing measuring instruments at the secondary windings of measuring current transformers, i.e. replacing electro-mechanical meters with less energy-consuming digital ones. Precise determination of the rated power of measuring current transformer is of utmost importance as the accuracy class and security factor are adjusted to that power.

As transformer-operated instruments for measuring active and reactive electric energy and maximum power, which within the system of half-indirect measuring are connected to the measuring current transformers' secondary windings, are dimensioned to comply with the rated secondary electric current of the measuring current transformers (1A or 5A). In [3-4] there is raised the issue of how the measuring instruments behave when the current through the measuring current transformers exceeds the specified one. The same goes for the measuring instruments within the direct measuring system. The base current in the latter is usually 10A with maximum current amounting to 40A, 60A, 80A or 100A, which are usually exploited in conditions where actual current values are twice as high as those of maximum ones.

The aim of this paper is to examine how measuring current transformers and direct and transformer-operated three-phase energy meters behave under underload and overload conditions, and determine the measuring error occurring thereby. Recent research regarding the accuracy of the measuring current transformers and energy meters consider mostly the impact of non-linear loads, i.e. the distortion of current and voltage, on the value of measurement error [5-9]. The influence of current and voltage THD has been studied separately for measuring current transformers, as well as for current transformers embedded in energy meters. Analyses presented show the significant influence of THD on phase error of both types of current transformers. This error is highly dependant on the frequency, so measuring the harmonics may be highly inaccurate. Generally, high error may be expected when load current is nonsinusoidal. Given the fact that literature does not provide enough information on the measurement errors under underload and overload conditions, the idea was to perform a detailed examination on this issue. The analysis presented in this paper includes separated laboratory testings on measuring current transformers, and direct and transformer-operated three-phase energy meters, under underload and overload conditions. Furthermore, the paper presents the results obtained through measurements in a 10/0.4kV substation.

2. Measuring Electric Power and Energy and Measurement Errors

The measurement system for electric energy and peak power at the voltage level of 0.4kV includes the measuring current transformers and transformer-operated instruments for measuring active and reactive power, and maximum power in transformer-operated measurement system. The measurement system also involves instruments for measuring active and reactive power, and maximum power within the direct measurement system.

In this paper, measuring current transformers of 50A/5A, 100A/5A, 150A/5A and 400A/5A current ratios (manufacturer FMT Zaječar) were tested, as well as the digital energy meters of ENEL Belgrade, i.e. two three-phase transformer-operated energy meters and three direct three-phase energy meters.

2.1. Measuring current transformer errors

Measuring current transformers includes current, phase and complex error.

Current error, g_i, results from the deviation of actual transmission ratio from its specified value. It is determined by [1, 2]:

$$g_i = \frac{m_n I_2 - I_1}{I_1} 100\% \qquad (1)$$

where $m_n = I_1/I_2$ is the indicated transformation ratio, and I_1 and I_2 are the primary and secondary windings currents.

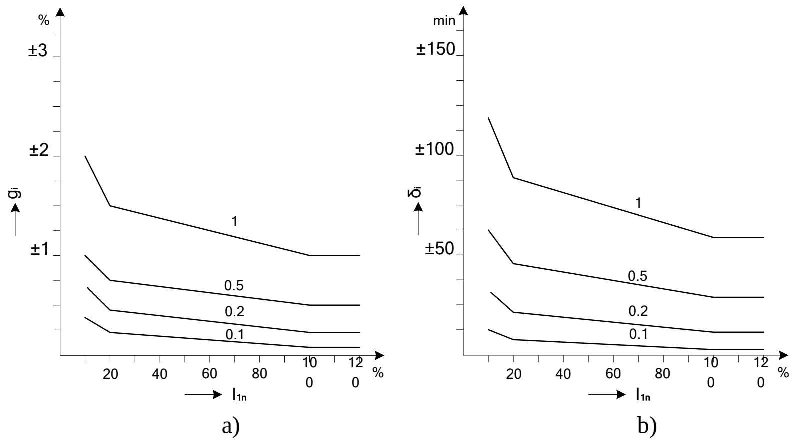
Phase error, δ_i, is defined by the angle between the secondary and primary current phasors. Phase error is positive if the secondary current leads the primary current.

Given that the distortion of the secondary current is possible at the increased primary current, which results from the saturation in the core, complex error can be defined with measuring current transformers as follows:

$$p_i = \frac{1}{\underline{I}_1} \sqrt{\frac{1}{T} \int_0^T (m_n i_2 - i_1)^2 \, \mathrm{d}t} \cdot 100\% \qquad (1)$$

The accuracy class of a measuring current transformer is equal to the absolute value of the current error expressed in percentage, at the specified load on the secondary winding and 120% of the rated primary current. Standard class accuracies are 0.1, 0.2, 0.5, 1, 3 and 5. Measurement of the electricity consumption does not include accuracy classes 1, 3 and 5.

Fig. 1 shows the limit values of the current and phase errors of measuring current transformers of accuracy classes 0.1, 0.2, 0.5 and 1, set out in [10]. Thus, for a transformer of accuracy class 1, limit of the current error is at 120% of the rated primary current and specified load on the secondary windings of the measuring current transformer.



a) b)

Fig. 1 Error value range: a) current error, b) phase error

2.2. Digital energy meters errors

Three-phase energy meters (direct and transformer-operated) are intended for measuring active and reactive electric energy in three-phase voltage system of the specified frequency of 50 Hz.

The accuracy of digital measurement groups is set out in [11]. Under the referential conditions, the percentage error should not exceed the value of the relevant accuracy class, Tables 1 and 2.

Table 1 Percentage error limits in single-phase and three-phase direct energy meters of accuracy class 1 (I_b is the base current, I_{max} is the maximum current)

Current values	Power factor	Error limit in %
$0.05\,I_b < I < 0.1\,I_b$	1	±1.5
$0.1\,I_b < I < I_{max}$	1	±1.0
$0.1\,I_b < I < 0.2\,I_b$	0.5(ind.), 0.8(kap)	±1.5
$0.2\,I_b < I < I_{max}$	0.5(ind.), 0.8(kap.)	±1.0

Table 2 Percentage error limits in single-phase and three-phase transformer-operated energy meters of accuracy class 1 (I_n is the rated current, I_{max} is the maximum current)

Current values	Power factor	Error limit in %
$0.02\,I_n < I < 0.05\,I_n$	1	±1.5
$0.05\,I_n < I < I_{max}$	1	±1.0
$0.05\,I_n < I < 0.1\,I_n$	0.5(ind.), 0.8(kap.)	±1.5
$0.1\,I_n < I < I_{max}$	0.5(ind.), 0.8(kap.)	±1.0

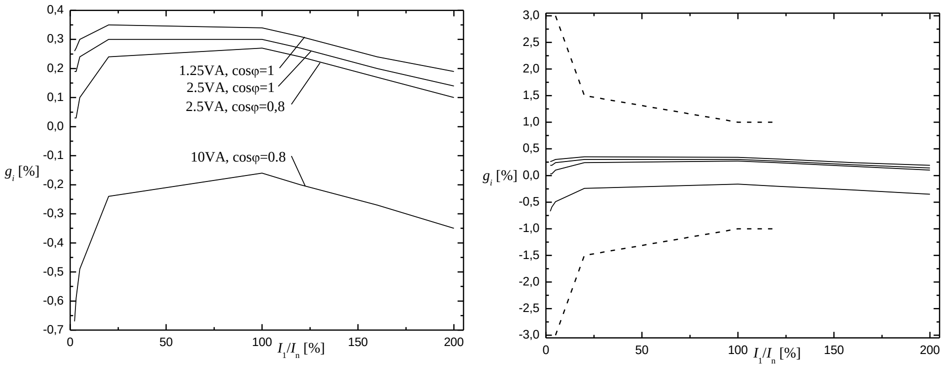
3. Measurement Results

3.1. Tests with measuring current transformers

The testing of measuring current transformers was performed in FMT ZAJEČAR, a measuring transformer company, on measuring current transformers of 50A/5A, 100A/5A, 150A/5A and 400A/5A current ratios. Three STEM 081 type transformers (50A/5A, 100A/5A, 150A/5A) and one STEN 081 type transformer (400A/5A) were used [3]. The testing was performed under the following conditions:

voltage: rated phase voltage,
current: from 0% to 200% of the rated current,
power factor: cosφ=1, cosφ=0.8(ind),
power: Sn=1.25VA, Sn=2.5VA, Sn=10VA, and
frequency: rated frequency of 50 Hz.

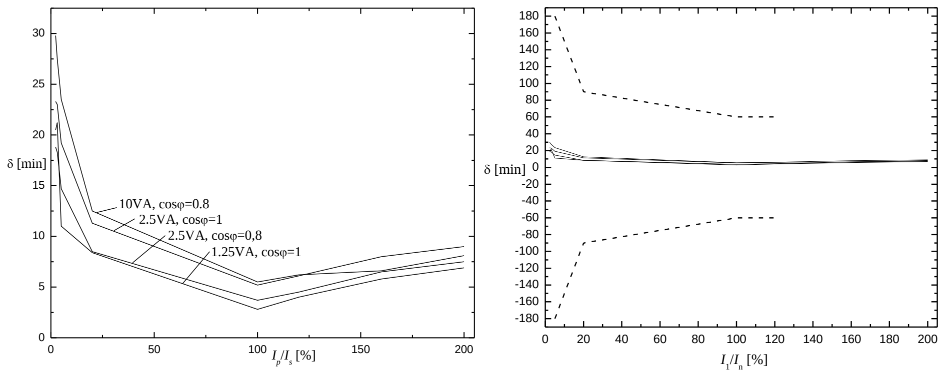
Current errors expressed in % and phase errors expressed in minutes at different current values were measured. All the measurements gave similar distribution of errors, regardless of the measuring current transformer ratio and the load on the secondary winding. Typical graphs that show current and phase errors with the primary current are given in Figures 2 and 3.



a) b)

Fig. 2 Variation in the current error with the primary current for different loads on the secondary winding: a) without the designated error limits, according to standard, and b) with the designated error limits, according to standard (broken line)

The results presented suggest that the current and phase errors are lower than the limit values, regardless of the value and power factor of the primary load, and the load on secondary windings of the measuring current transformer.



a) b)

Fig. 3 Variation in the phase error with the primary current for different loads on the secondary winding: a) without the designated error limits, according to standard, and b) with the designated error limits, according to standard (broken line)

Figure 4 presents the current error for the different current ratios of measuring current transformers and the 2.5VA load on the secondary winding at cosφ=1. It can be seen that the current ratio changes, for the same load at secondary winding does not affect the current error.

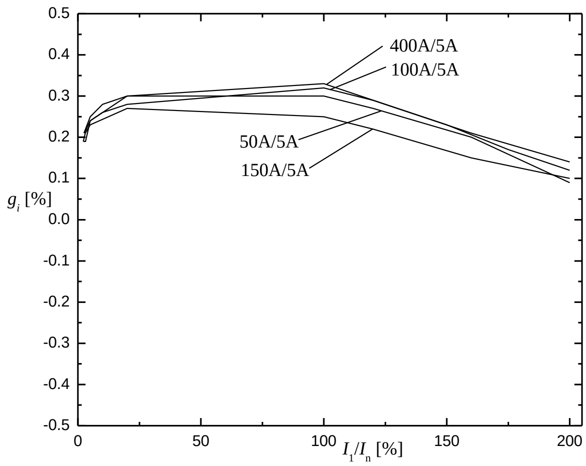


Fig. 4 Current error for the different current ratios of measuring current transformers

3.2. Testing of digital energy meters

Digital energy meters were tested using a control measurement system, i.e. ISKRAMATIC CATS SYSTEM [12, 13]. The testing was done on two three-phase transformer-operated energy meters (manufacturer ENEL Belgrade, type DMG2), and three direct three-phase energy meters, type DB2MG, of the same manufacturer [4].

The testing involved the following conditions:

voltage: specified phase voltage,

current: from 0.5 % to 200% of 5A rated current (transformer-operated energy meters), and from 2.5 % to 1000% of 10A base current (direct energy meters),

power factor: cosφ=1, cosφ=0.5 (ind.), cosφ=0.8 (ind.), cosφ=0.8 (kap), and

frequency: the rated frequency of 50 Hz.

Errors for active and reactive electric energy were measured, as well as for the maximum power.

Three-phase transformer-operated energy meters

Fig. 5 shows the measurement errors occurring at measuring active electric energy for two transformer-operated three-phase energy meters of the same type, while cosφ=1.

Fig. 6 shows the error occurring at measuring active energy for the different power factor values (cosφ=1, cosφ=0.5(ind), cosφ=0.8(ind), cosφ=0.8(cap)) using a three-phase transformer-operated energy meters.

A similar distribution of errors occurred when measuring reactive power.

The graphs in Figs. 5 and 6 show that errors occurring at measurements exceed the range of the error limits set out by a particular standard.

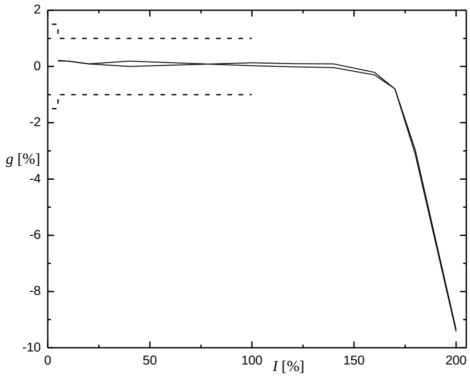


Fig. 5 The comparison of errors occurring at measuring active energy in two transformer-operated energy meters of the same type. Broken line presents the error range set out by standard

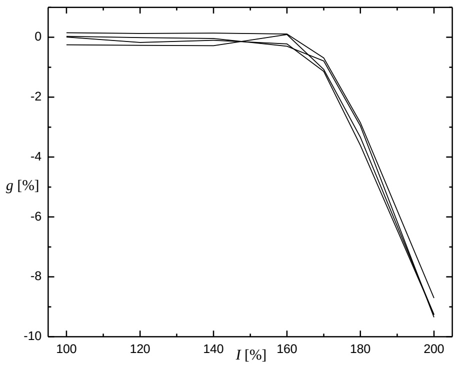


Fig. 6 Error occurring at measuring active energy at the different power factors

Direct three-phase energy meters

Base current for the tested direct measurement groups was 10A, whereas their maximum current was I_{max} = 60 A or I_{max} = 80 A. Given that the testing was done with the currents not exceeding 100A, error in active and reactive power measurements was within the error range set out by standard when measurements were performed in the energy meter with maximum current I_{max} = 80 A (Tables 3 and 4). The reason for this is a small difference between the maximum current of the meter and the maximum current used in the testing. In two meters with I_{max} = 60 A maximum current, this difference was substantially greater, which resulted in measurement errors (Tables 5 and 6).

Table 3 Percentage errors G % in direct energy meter, accuracy class 1 (active energy measurement, I_{max}=80A)

No.	1	2	3	4	5	6	7	8	9
I [A]	0.25	0.5	1	2	5	10	50	80	100
cosφ	1	1	1	1	1	1	1	1	1
Error limit [%]	±1	±1	±1	±1	±1	±1	±1	±1	±1
G %	-0.78	-0.27	0.07	0.19	0.03	0.05	0.31	0.35	0.65

Table 4 Percentage errors G % in direct energy meter, accuracy class 1 (reactive energy measurement at $\cos\varphi = 0.5$ (ind), $\cos\varphi = 0.8$ (ind), I_{max}=80A)

No.	1	2	3	4	5	6	7	8
I [A]	5	5	10	10	50	50	100	100
cosφ	0.5	0.8	0.5	0.8	0.5	0.8	0.5	0.8
Error limit [%]	±2	±2	±2	±2	±2	±2	±2	±2
G %	-0.33	-0.13	-0.2	-0.06	0.1	0.04	-0.03	0.17

Table 5 Percentage errors G % in direct energy meter, accuracy class 1 (active energy measurement, I_{max}=60A)

No.	1	2	3	4	5	6	7	8	9
I [A]	0.25	0.5	1	2	5	10	50	80	100
cosφ	1	1	1	1	1	1	1	1	1
Error limit [%]	±1	±1	±1	±1	±1	±1	±1	±1	±1
G %	1.47	0.71	-0.2	-0.3	-0.33	-0.53	-0.66	-2.19	-4.22

Table 6 Percentage errors G % in direct energy meter, accuracy class 1 (reactive energy measurement at $\cos\varphi = 0.5$ (ind), $\cos\varphi = 0.8$ (ind), I_{max}=60A)

No.	1	2	3	4	5	6	7	8
I [A]	5	5	10	10	50	50	100	100
cosφ	0.5	0.8	0.5	0.8	0.5	0.8	0.5	0.8
Error limit [%]	±2	±2	±2	±2	±2	±2	±2	±2
G %	-	-0,76	-	-1	-	-1,05	-	-4,64

Maximum power measurement error

Measurement of the maximum power error was done on transformer-operated three-phase energy meters at the current of 9A (180%) and cosφ=1. The results obtained show that peak power measurement errors at the load of 180%, cosφ=1, at a rated voltage and frequency on transformer-operated energy meters were –3.201% and –3.154%, respectively. Specifically, referential measuring instrument gave the value of 5.9362kW, whereas energy meters showed the value of 5.744kW and 5.748kW.

Laboratory studies do not fully correspond to real conditions, which is primarily due to the short testing period. In addition, the testing carried out in laboratory is done for a finite number of measurement points at certain values of currents and power load factors. In practice, current values and load type can be changed very quickly within a wide range of values, whereas the long-term current overloads on the measurement equipment cause it to overheat, which can affect measurement characteristics of the equipment and the value of measurement errors accordingly. Hence, the equipment tested in the laboratory was set up in a 10/0.4 kV substation for measurements in real conditions. Substation feeders on which major changes and long-term overloads can be expected were used in these measurements.

Measurements performed in a 10/0.4 kV substation

The measurements included setting up three measurement systems in a 10/0.4 kV substation. The complete measurement system comprised two transformer-operated energy meters DMG2, a single direct energy meters DB2MG ($I_{\max}$ = 80 A) and two sets of measuring current transformers with current ratios of 150A/5A 50A/5A, Fig. 7. Measurement systems were connected to each other so as to enable mutual load.

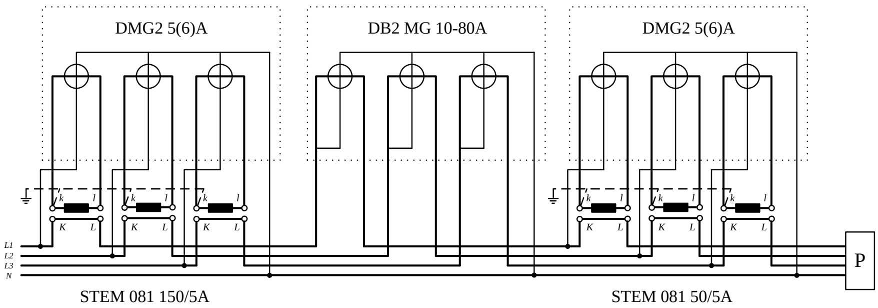


Fig. 7 Connection diagram of the measurement system in a 10/0.4kV substation

Earlier measurements conducted in a substation showed that changes in current were within the range of 70A–120A. These current values provide nominal operation of measuring current transformers of 150A/5A current ratio. On the other hand, transformers with 50A/5A current ratio operate under overload. Therefore, one of the transformer-operated energy meters (DMG2) operates in the nominal mode, whereas the other is overloaded. Direct energy meter DB2MG works with overload only partially. The average value of the phase voltage during measurement was 234V. The measurement of the consumed active and reactive energy, and maximum power over the period of 2h 45min was performed.

Table 7 shows the results of measurements obtained under the stated conditions. The results indicate a significant difference among the individual measurement systems. It can be assumed that the first measurement system, comprising measuring current transformers with 150A/5A current ratio and DMG2 transformer measurement group, gives the measurements with an error within an acceptable range (based on the results shown in previous subsections). Compared with these results, the relative deviation in measurement results for other two measurement systems was calculated. The results also point to significantly greater deviations than allowed.

Table 7 Percentage G % errors in direct energy meter, accuracy class 1 (active and reactive energy and peak power)

	DMG2+MCT 150/5	DB2MG	DMG2+MCT 50/5
W_a [kWh]	138.90	135.37	119.50
W_r [kVArh]	31.20	30.42	29.30
P_{max} [kW]	71.16	66.800	57.12
δW_a [%]	–	-2.54	-13.97
δW_r [%]	–	-2.5	-6.09
δP_{max} [%]	–	-6.13	-19.73

4. Conclusion

This paper presents the results of testing of the electric energy and maximum power measurement systems within the system of direct and half-indirect measurement at the voltage level of 0.4kV. Laboratory studies of measuring current transformers indicated that the current and phase errors, regardless of the power factor and primary load values, and the load on the secondary windings of the measuring current transformer, are below the limit values. However, it is important to note that, when selecting measuring current transformer, attention should be paid to the load on the secondary winding, as it can affect the measurement error.

Laboratory testing of transformer-operated energy meters revealed that the measurement errors of active and reactive electric energy and maximum power are:

- within the limits of accuracy class in overloads up to 70% (regardless of the load type),
- beyond the limits of accuracy class in overloads above 70%, i.e.:
  1) in 80% overloads the error ranges from 3.154% to 3.5%, and
  2) in 100% overloads the error exceeds 9%.

In direct energy meters, measurement results were within the limits of accuracy class when the value of the maximum current of the measurement group is slightly lower than the maximum operating current (up to 20%). Higher values of the operating currents result in similar error values as in transformer-operated energy meters.

Measurements conducted in substation confirm the results obtained in laboratory conditions. Increase in the measurement error can be expected under real conditions.

The results obtained imply that the energy meters introduce significant negative measurement error under overload conditions. This infers that in this operating mode, energy meters have lower values of both the consumed electric energy and maximum power, which can be interpreted as a loss.

Future analysis in this area will be focused on the influence of current and voltage THD to the measuring current transformer and energy meters errors.

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