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MEASUREMENT OF THE ENERGY PARAMETERS OF THE FREQUENCY CONVERTERS

ABSTRACT *In measuring the energy parameters of frequency converters, due to the nonlinear voltage and current waveforms, it is not possible to use standard measuring devices. One possibility is to use FFT analysis followed by a calculation of the individual powers. The paper presents the procedures, measurements and advantages of the measurements, which were made on the frequency converter with the voltage inverter at the industrial plant. Measurements were taken out in accordance with EN-6100-4-7. The paper presents not only the results of harmonic analysis of the input and output voltages and currents, but also the performance analysis and power factors. Interesting are also the waveforms of these variables and the changes in the out-put frequency, which was controlled with an industrial computer.*

Keywords: *energy parameters, frequency converters voltage, current, waveforms, measuring devices, FFT analysis, voltage inverter, harmonic analysis, power factor, frequency.*

1. INTRODUCTION

The number of frequency converters with the voltage inverters, which are common used in practice, is now already so large that it covers the whole range of possible control of electrical machines. It is assumed, that the trend of development

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and their use will continue, it must be paid full attention to the experience of the operation of these frequency converters. There are of course more levels, from which can be seen the application of inverters in variable speed drives. In principle it is possible to divide them in two main parts:

- Assessment converters according to their capabilities to fulfilled requirements of the technological equipment. There can be mentioned for instance their possibility of reversing the speed, torque, range of regulatory requirements for speed, accuracy, speed in static and dynamic state, the appropriateness of integrating technology into the overall power, the torque characteristic, diagram of the load, overload, etc.;
- Assessment converters with the conception of involving of power and control circuits, and by the whole design and implementation of the drive. An integral part is also evaluating how these properties are met and used in the praxis. Given the increasing installed capacity in these converters are also necessary to take to the problems of electromagnetic compatibility, especially on the impact of these converters to the power system. Of course, it is necessary to consider when choosing whether or not economic considerations, reliability, service, etc.

The choice of parameters according to the first point must be made in cooperation with the electrician and technologist. Also, the assessment of the work of the already installed converter must to make technology. Design of converters, mode of the controlling, circuit design, etc. is given by the manufacturer of the converter. When choosing new equipment, we can only change the electrical properties of converters already installed.

2. BASIC RELATIONS, ENERGETIC OF FREQUENCY CONVERTERS

Due to its design frequency converters are equipped with uncontrolled input rectifier. There-fore, it is not a problem the running of the converters with a good power factor of the first harmonic. In this case is going to the deformations of the current, which is collected from a power network. Today there are well-known the ways how to reduce the distortion voltage (for example, described in [1]). The result is a reduction of efficiency of the system (even though the converter has a very high efficiency). On the inverter output are distorted especially voltage waveforms. The main problem for assessing the energy parameters of the inverter is variable output frequency. In assessing the impact of the supply network is also the problem of variable impedance.

The following section provides only the most important relationships that have been used in processing. The full list is given in the literature [1].

We suppose that in a distribution system is in the point of common coupling (PCC) the power source, which can be expressed as Fourier series:

$$u(t) = \sum_{k=0}^{\infty} u_k(t) \tag{1}$$

where $u_k(t) = \sqrt{2} U_k \sin(k\omega t + \varphi_{uk})$ a $u_0(t) = U_0$ (2)

Currents of the appliances can be expressed similarly

$$i(t) = \sum_{l=0}^{\infty} i_l(t) \tag{3}$$

where $i_l(t) = \sqrt{2} I_l \sin(l\omega t + \varphi_{il})$ a $i_0(t) = I_0$ (4)

The basic definition of a power is:

$$p(t) = u(t) \cdot i(t) \tag{5}$$

Substituting (1) and (3) to (5) we get:

$$p(t) = \sum_{k=0}^{\infty} u_k(t) \cdot \sum_{l=0}^{\infty} i_l(t) \tag{6}$$

In practice it is defined a so-called active power, as a mean value of instantaneous power:

$$P = \frac{1}{T} \int_0^T p(t)dt = \frac{1}{T} \int_0^T \sum_{k=0}^{\infty} \sum_{l=0}^{\infty} u_k(t) \cdot i_l(t)dt \tag{7}$$

Other calculations we get the active power:

$$P = P_0 + P_1 + P_2 + ... = \sum_{k=0}^{\infty} P_k \tag{8}$$

Active power of the non-sinusoidal voltage and current is equal to the sum of harmonics active power of all harmonics order. This relation does not appear in literature. It is often assumed, that the voltage source is only sinusoidal. Also is assumed that voltage harmonics of other order are not present.

Apparent power, introduced as an auxiliary variable of computational reasons, like the harmonic voltages and currents is defined as the product of RMS voltage and current.

$$S = U \cdot I = \sqrt{\sum_{k=0}^{\infty} U_k^2} \cdot \sqrt{\sum_{l=0}^{\infty} I_l^2} \tag{9}$$

Reactive power indicates the level of energy, which is oscillating between the source and the appliance:

$$Q = \sum_{k=1}^{\infty} Q_k = \sum_{k=+}^{\infty} U_k I_k \sin \varphi_k \tag{10}$$

Because, that by the harmonic waveforms occur inequality:

$$S^2 \geq P^2 + Q^2 \tag{11}$$

Introduces the concept of distortion power, defined by:

$$D = \sqrt{S^2 - \left(P^2 + Q^2\right)} \tag{12}$$

Distortion power, like reactive power is useless part of apparent power. It is causing of an increase losses in the power system. Distorsion power also reduced the usability of the network and converters. In the nonharmonic circuit is not enough to insert only factor cos $\varphi_{(1)}$, but it is introduced of a true power factor Λ. (At present it is usually defined only as PF – Power Factor).

$$\Lambda = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2 + D^2}} = PF \tag{13}$$

Power factor PF and cos φ_1 not be confused (particularly for frequency converters with voltage inverter), because there are two very different values of power factors. It can occur in such states that require control system to cos $\varphi_1 \rightarrow 1$, but the power factor is very low.

To be able to assess the content of higher harmonics in the overall frequencies, it is used total harmonic distortion (THD). First, the individual harmonics are expressed in percentage terms (relative to the first harmonic) and also there are introduced so-called general factors, such as THD, which are defined as:

$$THD_U = \frac{\sqrt{\sum_{h=2}^{40} U_h^2}}{U_1} \quad \text{and} \quad THD_I = \frac{\sqrt{\sum_{h=2}^{40} I_h^2}}{I_1} \tag{14}$$

or

$$THF_U = \frac{\sqrt{\sum_{h=2}^{40} U_h^2}}{U} \quad \text{and} \quad THF_I = \frac{\sqrt{\sum_{h=2}^{40} I_h^2}}{I} \tag{15}$$

Note: Although the definitions are only slightly different, it can happen (especially by the values THD of the current), that the value THD (especially at indirectly frequency converters) can exceed 100%, but the value of THF must always be less than 100%.

3. MEASURING EQUIPMENT, MEASUREMENT, THE RESULTS OF MEASURING

From the relations in chapter 2 follows that we can not use a normal methods or standard measuring devices. It is necessary to use a special programs or measuring equipments for processing of the measurements. Problem is also the evaluation of measurement when we need assess the frequency converter as a whole system, and we need provide evaluation for input and output variables at once, but with time-variable frequency on the inverter output. Therefore it is not possible to evaluate the result of measurement from one measured period. The best solution is to use the standard [5]. Here is recommended a basic so-called three-second interval. Evaluation takes place after 10 periods of the fundamental frequency. Then the calculations are repeated for 3 seconds. In the graphic is this process captured in Figure 1.

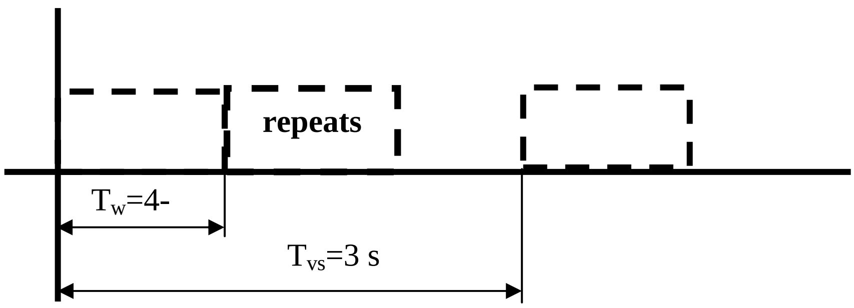


Fig. 1. Illustration of operation of the FFT analyzer in 3 s intervals

Measurements were made using a special program and sets of support programs. This ensures that the required measurements and subsequent calculations are carried out in accordance with the standard [5]. Input voltage was measured by the measuring voltage transformer, which was connected between the phases of R-S. Measured output voltage was scanned directly from output connectors on the converter. Measured currents were scanned from the measuring current transformers (input and output current). The actual recording of data was done using a computer. Galvanic insulation and the voltage adjustment are possible with measuring transducers (modules). Unlike conventional (and now available analyzers), we can select the characteristics of anti-aliasing filter, change the time window, change the measurement time due to the variable frequency drives, etc. We can measure also the output frequency.

In accordance with the standard measurements were taken as a "ten--minute measurement" and then as a 24-hour measurement. In the following is a list of variables that were analyzed for each measurement and graphically illustrated:

1. Values 1.harmonic of input voltage depending on the number of measurement (of time).
2. Values 3., 5., 7., 11.harmonic of input voltage depending on the number of measurement.
3. Total harmonic distortion of input voltage depending on the number of measurement.
4. Values 1.harmonic of output voltage depending on the number of measurement.
5. Values 3., 5., 7.harmonic of output voltage depending on the number of measurement.
6. Total harmonic distortion of output voltage depending on the number of measurement.
7. Values 1.harmonic of input currents depending on the number of measurement.
8. Total harmonic distortion of input currents depending on the number of measurement.
9. Values 1.harmonic of output currents depending on the number of measurement.
10. Values 3., 5., 7.harmonic of output currents depending on the number of measurement.
11. Total harmonic distortion of output currents depending on the number of measurement.
12. Active power on the input of converter P_{IN} depending on the number of measurement.
13. Reactive power on the input of converter Q_{IN} depending on the number of measurement.
14. Distortion power on the input of converter D_{IN} depending on the number of measurement.
15. Apparent power on the input of converter S_{IN} depending on the number measurement.
16. Active power of the first harmonic on the input of the converter P_{1IN} depending on the number of measurement.

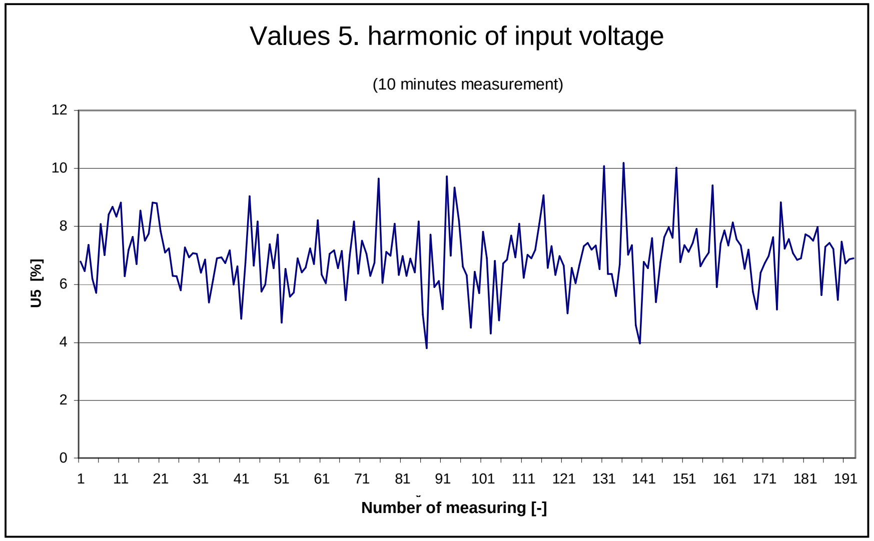
17. Reactive power of the first harmonic on the input of the converter Q_{1IN} depending on the number of measurement.
18. Power factor of the first harmonics cos φ_{IN} on the input of the converter.
19. Power factor PF_{IN} (total) on the input of the converter.
20. Active power on the output of converter P_{OUT} depending on the number of measurement.
21. Reactive power on the output of converter Q_{OUT} depending on the number of measurement.
22. Distortion power on the output of converter D_{OUT} depending on the number of measurement.
23. Apparent power on the output of converter S_{OUT} depending on the number of measurement.
24. Active power of the first harmonic on the output of the converter P_{1OUT} depending on the number of measurement.
25. Reactive power of the first harmonic on the output of the converter Q_{1OUT} depending on the number of measurement.
26. Power factor of the first harmonics cos φ_{OUT} on the output of the converter.
27. Power factor PF_{OUT} (total) on the output of the converter.
28. The time course of the frequency converter output frequency.

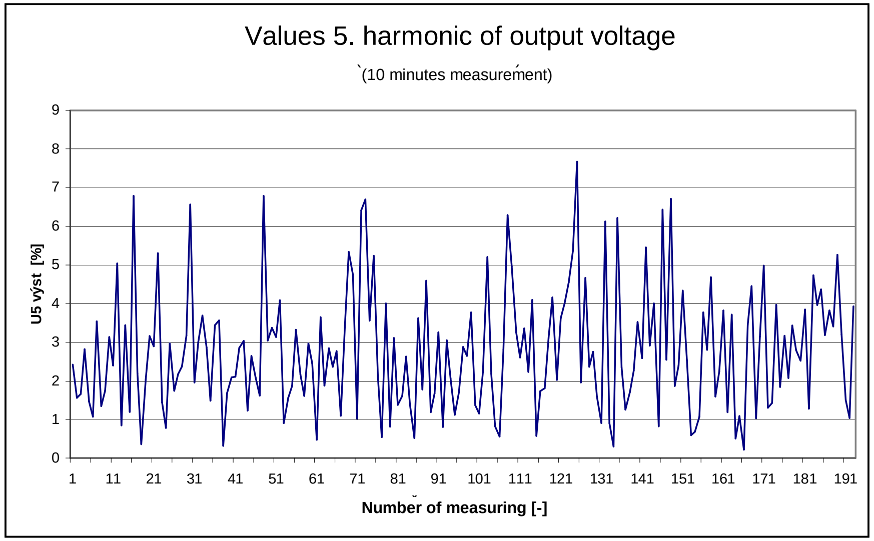
The ten-minute measurements were measured as continuous. Within ten minutes we obtain 200 three-second intervals. During the 24-hour measurement followed always after 3 seconds measurement the 57 seconds pause. In 24 hours we got the 1440 samples.

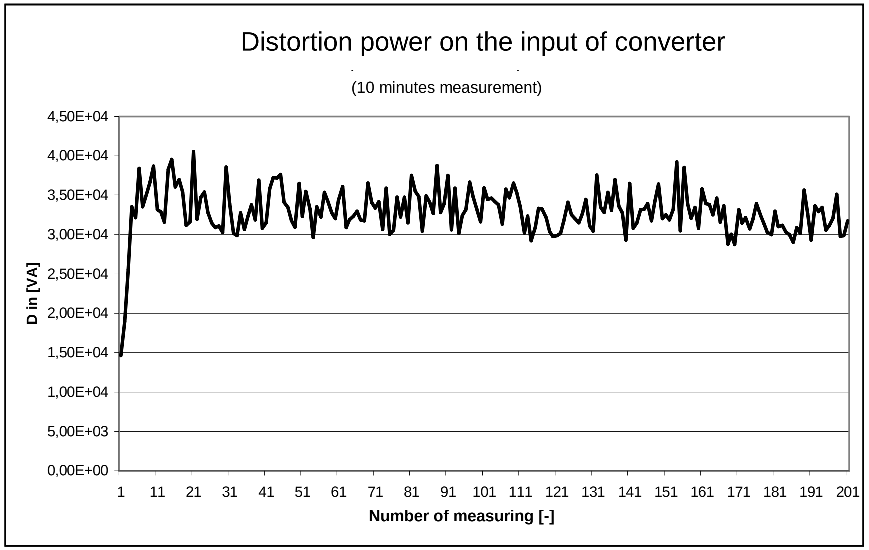
4. EXAMPLES OF MEASURED VALUES

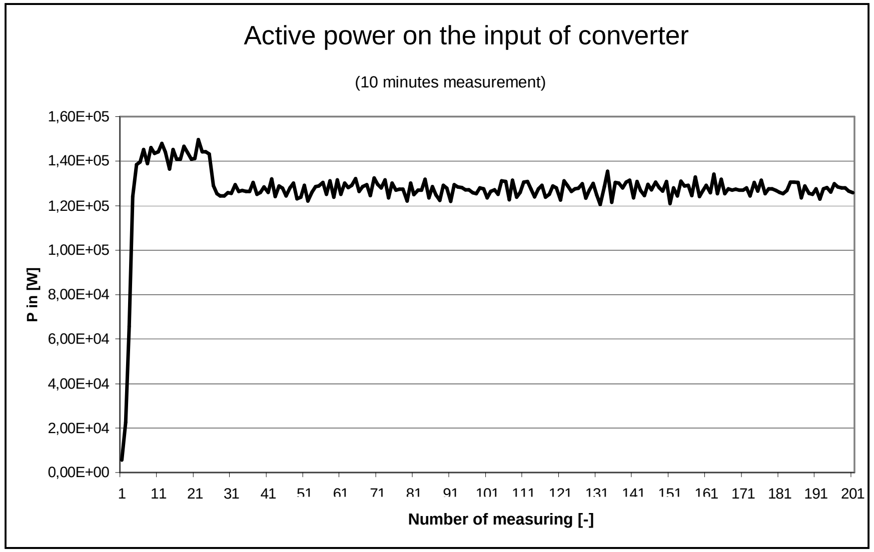
From the list of measurements shows, that it is possible to obtain a comprehensive overview of the operational characteristics of converters in a long time zone. The following figures are provided some interesting graphs, which were obtained by the measuring. The complete set of measurements is stored at the authors work.

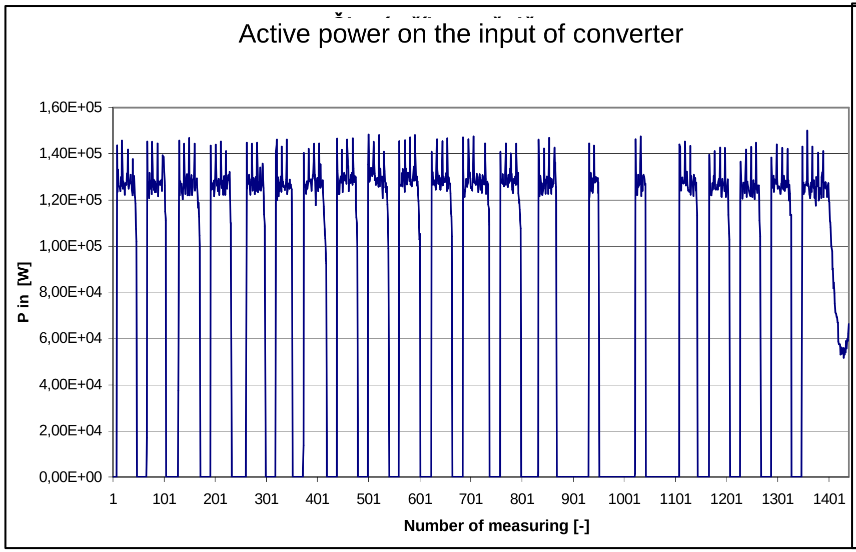
(They shows the parts of the work, where were measured the electrical characteristics of the AC Inverter, which is installed in a pumping station. One of the objectives was to verify, whether the inverter can operate in these conditions and verify the use of the frequency range of the converters.)


Values 5. harmonic of input voltage
(10 minutes measurement)
U5 [%]
Number of measuring [-]


Values 5. harmonic of output voltage
(10 minutes measurement)
U5 výst [%]
Number of measuring [-]


Distortion power on the input of converter
(10 minutes measurement)
D in [VA]
Number of measuring [-]


Active power on the input of converter
(10 minutes measurement)
P in [W]
Number of measuring [-]



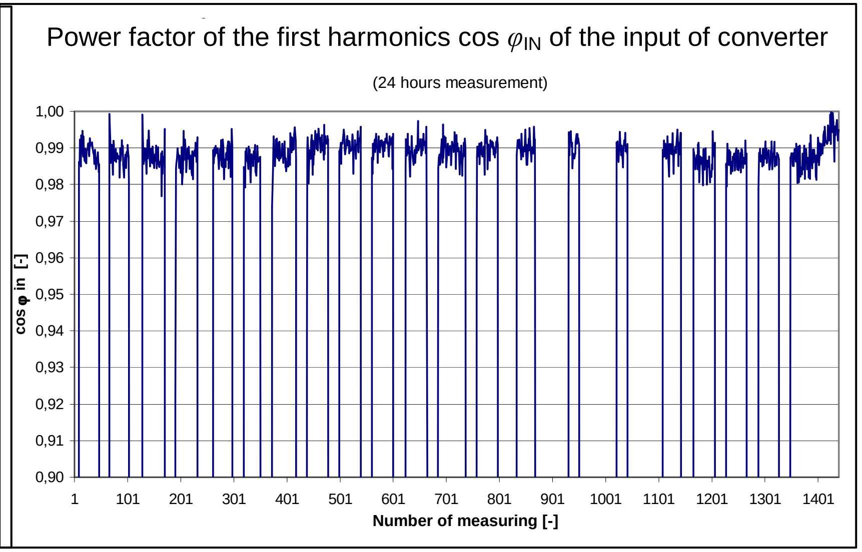


Fig. 2. Examples of measured values

These examples show that for a full assessment of the performance of the frequency converter (its energy parameters) requires a relatively large set of measurements and subsequent graphs. The graphs shows, that the converter works with very good cos φ_1, but also with very good a power factor PF. In this case it is caused by the reactor, which is connected on the input of the converter. The reactor significantly improves the shape of the current, which load the network (see values of 5.harmonic of input currents), but worse is the voltage on the input terminals of the inverter (see values of 5. harmonic of input voltage). When we used the reactors, it is necessary to observe not only the value of the voltage drop of the fundamental harmonic, but also a total distortion of the voltage waveform. Deformation of voltage at the input of reactors are not recorded, because in the plant have been installed filters of fifth harmonic.

Other interesting information is the output frequency for both cycles. The control system stabilizes a constant pressure in the pipeline. After the connecting there was a slight decline in the frequency and subsequent operation of frequency converters with an almost constant rate for 10-12 minutes. Then is increasing the output frequency (about 1 minutes) and subsequent is repeating the process every 10-12 minutes. Followed by a 20 minute delay (the converter is disconnected from the power) a repetition of the original cycles. Only the end of the 24-hour measurements has the results changed. During operation, the inverter and the motor was loaded to 120, respectively. 130% of installed capacity, but the system functioned without any failure.

5. CONCLUSION

In this paper is shown, which parameters can be used in assessing of the energy parameters of frequency converters and how to analyze them. The measurement is in an accord with the standard [2]. The calculations are based on a previously mentioned relation in this paper. Because it is a measurement and the processing of large amounts of data, it is advisable to use special programs.

This work has been supported by the project No. GAČR 102/09/1164.

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Manuscript submitted 29.11.2011

POMIAR PARAMETRÓW ENERGII PRZETWORNIKÓW CZĘSTOTLIWOŚCI

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STRESZCZENIE *W pomiarach energii przetworników częstotliwości, w wyniku nieliniowego przebiegu napięcia i prądu, nie jest możliwe użycie standardowych przyrządów pomiarowych. Jedyną możliwością jest wykorzystanie analizy FFT i następnie obliczenie poszczególnych mocy. Artykuł przedstawia procedury, pomiary i zalety pomiarów, które były wykonane na przetwornikach częstotliwości z przekształtnikiem napięcia w zakładzie przemysłowym. Pomiary były pobierane zgodnie z EN-6100-4-7. Artykuł przedstawia nie tylko wyniki analizy harmonicznej napięć i prądów wejściowych i wyjściowych, ale także analizy działania i współczynników mocy. Interesujące były także przebiegi tych zmiennych i zmiany częstotliwości wyjściowej, która była sterowana za pomocą komputera przemysłowego.*