

MEASUREMENT OF PERFORMANCE PARAMETERS IN SYSTEMS WITH FREQUENCY INVERTERS

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Abstract

Speed control of AC (alternating current) motors and generators with frequency inverters is becoming increasingly popular, especially due to the decreasing cost of the inverters. This is a positive trend in terms of user comfort, as well as in terms of energy savings. However, besides the undeniable advantages of this technology, it also brings some difficulties arising from the non-harmonic waveforms of the inverters output voltages. This is reflected, for example, in the requirement for greater accuracy in the measurement of electrical input/output power. Conventional wattmeters remain available, but they are mainly designed to measure harmonic waveforms of circumferential parameters. The article experimentally verifies six principles of power system performance measurement and compares them with the YOKOGAWA WT300E digital reference wattmeter, which is specially designed for non-harmonic waveform measurements. The comparison shows that conventional power meters differ from the reference wattmeter up to 12.5%. A set of three conventional wattmeters presents the least deviation from the reference meter, with the range of 0.17 to 7.2%.

Key words: frequency inverter; wattmeter; power output; asynchronous motor/generator.

INTRODUCTION

The issue of the three-phase system output measurement was described in (*Dufek & Fajt, 1974*). Measurement applied to a low-output power source with a bladeless turbine and a low voltage synchronous generator was presented in (*Vondrášek & Dlabal, 2016*). (*Gyarfas & Rapant, 1991*) described measurement of output and transmitted energy according to IEEE standards. (*Ďaďo & Sedláček, 1987*; *Novák & Novák, 2009*) extended the measurements to non-harmonic waveforms of circumferential parameters. (*Chyský, Kořínek, Novák & Novák, 2013*; *Novák, Chyský & Kořínek, 2015*) utilized it for networks with non-harmonic parameters. (*Han, Luo, Hou, Su, Yuan, Liu & Guerrero, 2018*) paid attention to effective inverter control for photovoltaic power system. For the operation of wind power plants, the use of inverters is necessary due to the inconstant speed of the generators; the quality of the supplied energy is evaluated according to IEEE Directives as described in (*Emanuel, Schellschmid, Wachtel, & Adloff, 2009*). A similar situation occurs with small hydropower plants or with the use of pumps as turbines for energy recovery in water distribution networks (WDN). The main interest of the paper is the comparison of measurement results between meters of different constructions.

MATERIALS AND METHODS

Electronic inverters are used to run electric motors with AC (alternating current) and DC (direct current) power systems in regulated drives and in the operation of alternative energy sources. Electric machines with alternating current multiphase systems are used as conventional energy sources with constant speed. The development of power electronics enabled their use in wind power plants and in drives with speed control. The multiphase current system allows creation of a so-called rotating magnetic field.

Alternating machines with a rotating magnetic field are easier to design and cheaper to manufacture compared to DC machines. For speed control, the frequency of the power supply system needs to be changed using inverters. Besides the undeniable advantages, this technology also brings some pitfalls. One of them is the occurrence of non-harmonic waveforms of the output voltages and currents of the inverters.



This is manifested, for example, in the requirement for greater accuracy in the measurement of electrical input/output power. Modern digital devices are already available, but their prices are high. Conventional wattmeters remain available, however they are largely designed to measure harmonic waveforms of circumferential parameters. The article compares the results of six different principles of measuring electrical input, or output power of asynchronous machine in motor, or generator operation. An asynchronous machine AP112M-2s, manufactured by MEZ Mohelnice, was used for the experimental verification. It was mechanically connected to the radial centrifugal pump META Plus 5, manufactured by ISH Pumps Olomouc, which is a part of a hydraulic test circuit described in (*Polák*, 2019) A heavy duty frequency inverter Frecon LSLV0055S100-4EOFNS, manufactured by LS Industrial Systems, with power output of 5.5 kW was used to control the operation. The whole set allowed to measure the performance characteristics in both motor and generator mode, when the pump was operated in pump and also in reverse turbine operation.

Measuring sets

The first of the six measuring sets consisted of three individual electrodynamic wattmeters for harmonic power system. A diagram of connection of the set between the asynchronous machine and the inverter is presented in Fig. 1a (the set is labelled 3W in graphs of performance parameters). Next measuring set was based on the principle of measurement with one three-phase wattmeter described in (*Vondrášek & Dlabal, 2016*). Its connection is shown in Fig. 1b (it is labelled Ganz in graphs).



Fig. 1 a) Connection of 3 wattmeters Ganz HEWa-2 with artificial zero point, b) three-phase wattmeter Ganz HEWa-b with one current circuit.

The third device was a combined measuring set Metra QN10 with a voltmeter, ammeters in each phase and a three-system wattmeter (see Figure 2a). Its connection was similar to the set of the three wattmeters with artificial zero point jointed to the measuring device. Next device was a combined measuring set Metra QW2j with a voltmeter, ammeters in each phase and a two-system ferodynamic wattmeter connected similarly as the pair of wattmeters in Aron's scheme according to (*Brandolini & Gandelli, 2009*), as shown in Figure 2b.



Fig. 2 a) combined measuring set QN10 with three-system wattmeter, b) combined measuring set QW2j with two-system wattmeter



The fifth meter is a digital wattmeter YOKOGAWA WT300E (*Zhou, Su, Li, Fang, & Cheng, 2018*). This wattmeter is specially designed to measure the performance of non-harmonic waveforms. In view of this, it was designated as a reference meter. The variant 3V-3A was chosen out of the possible configurations proposed by the manufacturer, and it is presented in Fig. 3.



YOKOGAWA

Fig. 3 Digital wattmeter YOKOGAWA WT300E, configuration 3V-3A

The five above described devices were complemented by frequency inverter Frecon, which displayed the active electrical power output. The monitored data were included for comparison with other meters. The built-in algorithm for calculating invertor output power has not been published by the manufacturer. However, it is possible to assume the use of theoretical principle for determining the instantaneous power output p according to:

(1)

(4)

 $p = u \cdot i$

where u is instantaneous value of voltage, i is instantaneous value of current.

Evaluation of periodic signal of period *T* and determination of mean power output *P* lead to differential equation (2) according to (*Chyský*, Kořínek, Novák & Novák, 2013)

$$P = \frac{1}{T} \int_0^T u(t) \cdot i(t) \cdot dt$$
⁽²⁾

For numerical evaluation, the integral was replaced by finite number of time periods k forming period T

$$P = \frac{1}{T} \sum_{i=1}^{i=k} u_i \cdot i_i \cdot \Delta t \tag{3}$$

where Δt is period of sampling of instantaneous values of circumferential parameters u and i. At the same time, equation (4) applies:

 $T = k \cdot \Delta t$

For correct evaluation, it is necessary for the sampling frequency to correspond to at least twice the frequency of the measured signal.

For complete information, mechanical output power data on the motor shaft measured by torque sensor Magtrol TMB 307/411 were added to the output power characteristics.

RESULTS AND DISCUSSION

The test circuit was designed to operate the asynchronous machine in pump mode as a motor, thus it acts as an appliance. In turbine mode, the asynchronous machine operates as a generator.

The measurement of the performance characteristics in the pump mode was carried out at a constant speed of n = 2,950 rpm. During the measurement, the water flow was throttled by a control valve at the discharge from the pump. At the same time, the phase currents between the inverter and the asynchronous motor and the electrical input of the set were measured in steady states. The courses of the monitored parameters depending on the pump flow are presented in Fig. 4.





Fig. 4 Input and output powers and phase currents of asynchronous machine depending on pump flow.

The mechanical input of the pump increased with the flow rate – see the MAGTROL curve in Fig. 4 on the left. A similar energy flow situation occurs when the heat pump is powered from the inverter used in the dehumidification experiment according to (*Zhou, Su, Li, Fang, & Cheng, 2018*).

The course of the power input of waterpump was linear, which corresponds to the theoretical assumption. The electric input power of the motor had similar trend, only it was shifted upwards by the energy losses of the pump and the engine. The input power data measured by the various meters had deviations in the range of 3.2 to 10.7%. The biggest deviation of 10.7% was recorded by the Ganz HEWa-b three-phase wattmeter with one current-device at zero pump flow rate. On the other hand, the 3W set presented the best match with the reference meter, with measured values differing from the reference values by 0.40 - 1.17%. The increase of the asynchronous motor current from the initial value in the monitored load range was approximately parabolic. The course corresponded to the theoretical assumption for loading an asynchronous motor with an initial current value different from idle. The difference occurred due to the motor load by pump losses at zero flow rate. The values of phase currents measured by different meters differed from each other minimally – in the range of 4.9 to 10.2%. The greatest percentage differences were recorded at zero pump flow rate and smallest used currents. Turbine mode measurements were performed at constant feed pump settings, while power outputs and currents at the asynchronous machine in generator mode were monitored. The loading was carried out

by gradual reduction of the shaft speed by means of an inverter placed between the asynchronous machine and the load. The measured power outputs and electric currents depending on the shaft speed are shown in Fig. 5. A similar energy flow situation occurs in wind powerplants and the standardized IEEEE energy quality measurement is used in paper by (*Emanuel et al., 2009*).



Fig. 5 Power outputs and phase currents of asynchronous machine depending on shaft speed.



When measuring the output power of the asynchronous generator, the 3W set presented the lowest deviation from the reference meter, namely in the range of 1.4 to 7.2%. On the other hand, the QN10 set showed the largest deviation of 60.8% at the lowest speed and 28.7% at the highest speed. In the remaining measured range, the deviation was in the range of 1.1 to 14.1%, similar to other meters. The phase currents of the asynchronous generator decreased with machine speed. The biggest differences between the data from the ammeters were in the area just above the highest output of the asynchronous generator and at the highest speed of the machine when the deviation reached 20.9%. In the remaining monitored speed range, the current deviations oscillated between 10 to 12.5%. The current drop with increasing speed was conditioned by setting the inverter to the so-called full field of the asynchronous machine. The monitored speed range of the set corresponded to the frequency of the current system f_1 which was lower than the nominal one. To prevent over-saturation of the magnetic circuit of the asynchronous machine, a reduced voltage was applied and a constant U_1/f_1 ratio was roughly maintained, so the voltage raised as the speed increased. A lower current was sufficient for a defined output power at a higher voltage.

CONCLUSIONS

Experimental measurements in circuits with non-harmonic waveforms showed that only currents can be measured reliably with conventional ammeters designed for harmonic waveforms. This is partly due to the imperfect symmetry of the set and the load. Combined meters equipped with ammeters presented data comparable to the reference digital meter.

In the case of power output measurement, it appeared that analogue meters compared to the reference digital one were lagging behind. The results of the set of three individual phase electrodynamic wattmeters with an artificial zero point (3W) were the closest to the results of the reference meter, with deviation between 0.17 to 1.17% for motor mode and 1.4 to 7.2% for generator mode. Combined meters QN10 and QW2j were equipped with multi-system wattmeters but with ferromagnetic components of magnetic circuits. This fact distorted the measurements at higher frequencies that occurred in circuits with non-harmonic waveforms of circumferential parameters. This was most evident in the generation operation of the asynchronous machine, where the deviations in the performance measurements from the reference meter were the greatest, depending on the measuring apparatus – up to 60.8% for QN10 meter.

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