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Analysis of the energy consumption by an industrial robot for the angular movement of individual axes

***Abstract**. The article presents a computer system for the measurement and recording of voltage waveforms and supply current of the Kawasaki industrial robot. The system was realized using specialized voltage and current transducers and a PC computer with a measuring card. Measurement tests were carried out using the implemented computer system. The voltage and supply current characteristics were recorded for one static state and six dynamic states of an industrial robot. In the static state, the motors of all axes were braked and the robot manipulator did not move. In dynamic states there was an angular motion of one selected axis, and the motors of the remaining axes were braked. An analysis of the electric energy consumption by the robot was performed with the angular displacement of individual axes for a given speed of motion.*

***Streszczenie.** W artykule przedstawiono komputerowy układ do pomiarów i rejestracji przebiegów czasowych napięcia oraz prądu zasilającego robota przemysłowego Kawasaki. Układ zrealizowano z wykorzystaniem specjalistycznych przetworników napięcia i prądu oraz komputera PC z kartą pomiarową. Przeprowadzono badania pomiarowe i zarejestrowano przebiegi czasowe napięcia i prądu zasilania robota dla jednego stanu statycznego oraz sześciu stanów dynamicznych. W stanie statycznym silniki wszystkich osi były zahamowane i manipulator robota nie przemieszczał się. W stanach dynamicznych występował ruch kątowy jednej wybranej osi przy zahamowanych pozostałych osiach. Przeprowadzono analizę zużycia energii elektrycznej przez robota przy kątowym przemieszczaniu poszczególnych osi dla zadanej prędkości ruchu. (**Analiza zużycia energii przez robota przemysłowego przy kątowym ruchu poszczególnych osi**).*

Keywords: industrial robot, computer measuring system, non-linear receiver.
Słowa kluczowe: robot przemysłowy, komputerowy system pomiarowy, odbiornik nieliniowy.

Introduction

Industrial robots are widely applied for welding, spray coating, mounting of various elements, including screws, packaging, sorting and moving objects. The usefulness of robots is motivated by their technological characteristics, such as speed, accuracy and repeatability of certain production stages, and also by economic factors, such as a possibility to increase production and often to reduce unitary cost at the same time [3, 8, 10, 14].

An important aspect of the robot control is to optimize its operation by keeping energy consumption to the minimum. This issue is complex and involves many levels of analysis. This paper aims to make a contribution to the problem by analysing energy consumption by a robot Kawasaki FS03N for the case of angular motion of the particular axes at a prescribed speed. For the sake of developing a computer measuring system, a methodology was analysed of measurements in transducer drives and non-linear circuits as well as problems of measuring non-linear quantities [5, 6, 11, 12, 13].

The robot under scrutiny is treated as a non-linear power receiver consisting in its strong-current part of a rectifier circuit, a DC circuit and six transducers supplying power to the motors of the mechanical manipulator. A pneumatic claw of the manipulator with height compensation is supplied from a separate circuit, which does not influence directly the operation of the circuits supplying the motors of the robot's particular axes [7, 8].

Power components for a non-linear receiver

The apparent power consumed by a non-linear single-phase receiver with a sinusoidal voltage supply and distorted current is [1, 2]:

$$S = U \cdot I \tag{1}$$

where: U - effective value of the sinusoidal phase voltage, I - effective value of the deformed phase current.

The distorted phase current is expressed as [1, 2, 6]:

$$I = \sqrt{I_1^2 + \sum_{n>1}^{\infty} I_n^2} \tag{2}$$

where: I_1 – effective value of the fundamental harmonic current, I_n – effective value of n-th harmonic current, n – harmonic order.

The active power supplied to a non-linear single-phase receiver is [1, 2]:

$$P = \frac{1}{T}\int_0^T u \cdot i \, dt = U \cdot I_1 \cdot \cos\varphi_1 \tag{3}$$

where: P – the active power, T – period of time function, u, i – the waveforms of the phase voltage and the phase current, φ_1 – the phase shift angle between the voltage and the fundamental harmonic current.

The value of active power depends only on the fundamental current harmonic. Higher harmonics of distorted current do not transform active power at sinusoidal supply voltage. The phase shift between the supply voltage and the fundamental harmonic of the distorted current is responsible for the consumption of reactive power by the receiver. This power is referred to as the reactive power Q_1 of the fundamental harmonic and is defined as:

$$Q_1 = U \cdot I_1 \cdot \sin\varphi_1 \tag{4}$$

Taking (1) into account, the apparent power S_1 of the fundamental harmonic is:

$$S_1 = U \cdot I_1 \tag{5}$$

Using the formulas for active power and apparent power, it is possible to obtain the phase shift factor for the non-linear receiver [2, 6]:

$$\cos\varphi_1 = \frac{P}{S_1} = \frac{P}{\sqrt{P^2 + Q_1^2}} \tag{6}$$

Higher harmonics of the distorted current are responsible for the occurrence of distortion reactive power *D*. This power is taken into account when the power factor λ_{nl} of the non-linear receiver is calculated by means of the following formula [2, 6]:

$$\lambda_{nl} = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}} = \frac{P}{\sqrt{P^2 + Q_1^{\ 2} + D^2}} \tag{7}$$

The power components for the non-linear receiver represented graphically as vectors can be seen in Fig. 1.

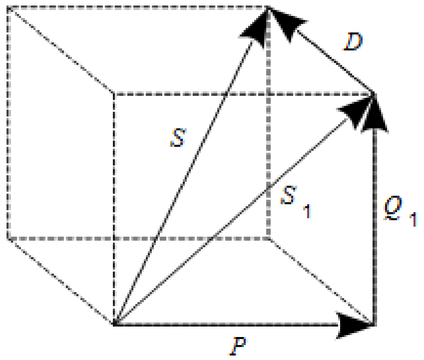

Fig. 1. The power component vectors of the non-linear receiver [2]

A computer measuring system for the robot Kawasaki

In order to measure time waveforms of supply voltage and current of the robot Kawasaki type FS03N, a computer system was developed consisting of measuring transducers, a measuring card and a PC with recording and visualization software.

The robot is normally supplied by single-phase voltage of the value U=230V and frequency f=50Hz. Since the strong-current circuit has to be galvanically isolated from the measuring circuit, two transducers manufactured by LEM with appropriately selected ranges were used: transducer LV25-P in the voltage circuit and LA55-P in the current circuit. Selected parameters of the measuring card and measuring transducers are specified in Table 1.

Table 1. The parameters of the measuring card and measuring transducers [9]

Designation	Names and selected parameters
Adlink 9118L	Measuring card: channels 16 single-ended or 8 differential resolution 12-Bit conversion time 3 μs maximum sampling rate 100 kS/s overvoltage protection continuous ±35 V input impedance 1 GΩ trigger modes software, pacer, and external trigger
LV25-P	LEM voltage transducer: measurement range 100V, 500V measurement accuracy ± 0,8 % linearity ± 0,2 % response time 40 μs
LA55-P	LEM current transducer: measurement range 10A measurement accuracy ± 0,65 % linearity ± 0,15 % response time 40 μs

Outputs of the measuring transducers were connected to the external module of the measuring card Adlink 9118L installed in the PC. The measuring card is equipped with a 12-bit A/C transducer with the maximal sampling frequency of 100 kHz. The card offers a possibility of simultaneous recording of up to eight bipolar channels. A block diagram of the computer measuring system is presented in Fig. 2

The software used for recording and visualizing the supply voltage and current waveforms was DasyLab [4]. The measuring signals from transducers are read by two channels of the card Adlink 9118L and subsequently processed by the software DasyLab. The processing sequence consists of calibrating the values of voltage and current in order to represent them as real values, read-out by the digital meter module, calculations of selected quantities, graphic presentation of the time waveforms as well as saving the results in a file, in accordance with the DasyLab standard. A block diagram of the signal processing system is presented in Fig. 3.

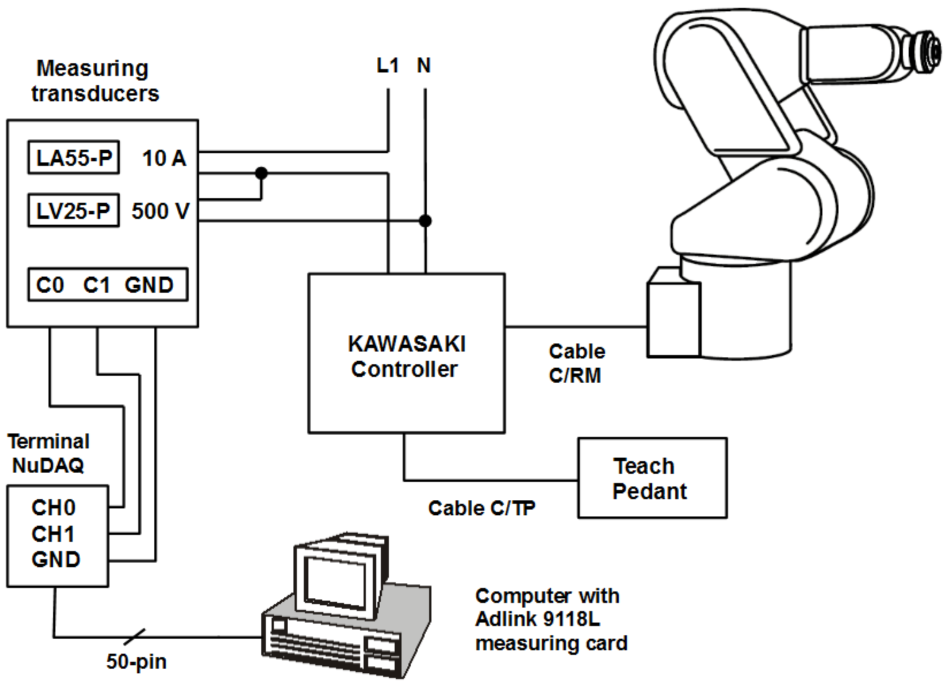

Fig. 2. The block diagram of the computer measuring system for voltage and current of the Kawasaki FS03N robot

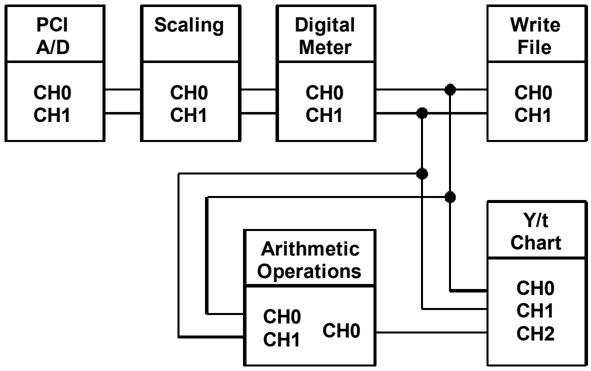

Fig. 3. The block diagram of the voltage and current measurement signal processing system of the Kawasaki FS03N robot

Measuring study

The measuring study of the robot Kawasaki involved recording time waveforms of supply voltage and supply current for selected working conditions, which included one static state and six dynamic states.

In the static state, the motors of all the axes were stopped and the robot manipulator did not move. In each of the dynamic states the angular motion occurred along one axis, with the other ones stopped. The various working conditions are presented in Table 2, and the range of the displacements of the robot axes during the measurements are presented in Table 3.

Table 2. The various working conditions of the robot during the measurements

Working conditions	Robot axes					
	JT1	JT2	JT3	JT4	JT5	JT6
Static state	off	off	off	off	off	off
Dynamic state JT1	on	off	off	off	off	off
Dynamic state JT2	off	on	off	off	off	off
Dynamic state JT3	off	off	on	off	off	off
Dynamic state JT4	off	off	off	on	off	off
Dynamic state JT5	off	off	off	off	on	off
Dynamic state JT6	off	off	off	off	off	on

Table 3. The range of the displacements of the robot axes during the measurements [7, 8]

Robot axes	Range of displacements
JT1	from 0 to 160°
JT2	from 0 to 120°
JT3	from 0 to -150°
JT4	from 0 to 360°
JT5	from 0 to 135°
JT6	from 0 to 360°

The supply voltage vs. time, the supply current vs. time and the active power vs. time curves recorded at the static state and at the dynamic states are presented in Figs 4-6. The calculations of power and energy consumed by the robot Kawasaki FS03N at the static state and at the dynamic states were carried out by means of the software DasyLab. First, mathematic formulas defining the components of power and energy were implemented in the computation modules of the software. The results of the calculations in the form of the time characteristics of active energy and distortion reactive energy are presented in Figs 7-8.

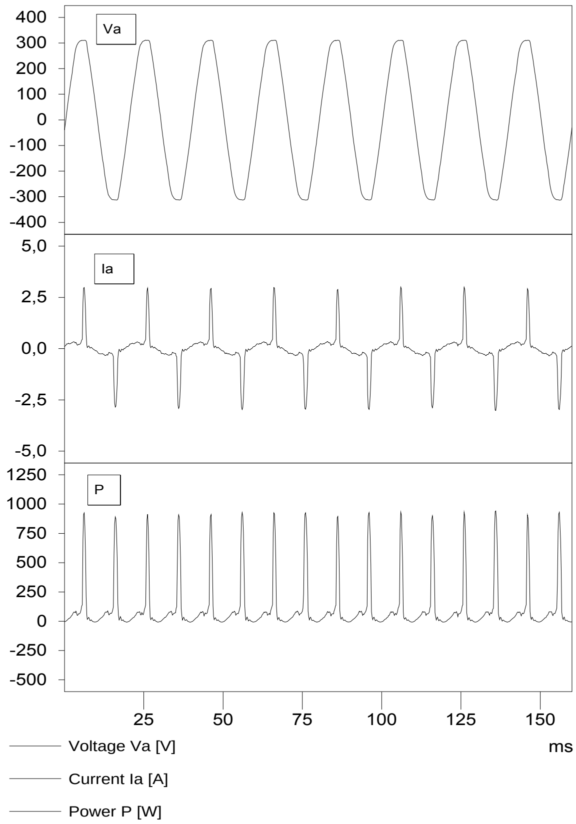

Fig. 4. The time characteristics of the supply voltage, the supply current and the active power of the Kawasaki robot at the static state

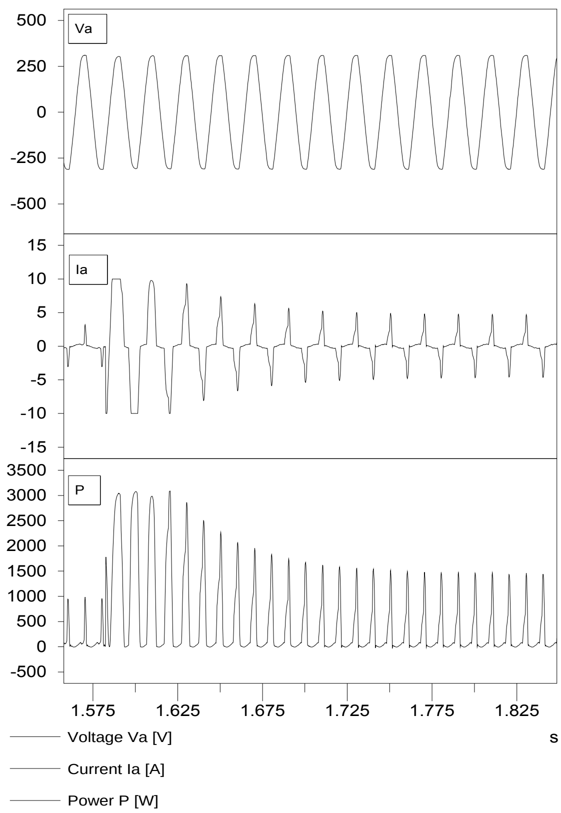

Fig. 5. The time characteristics of the supply voltage, the supply current and the active power of the Kawasaki robot at moving the JT1 axis

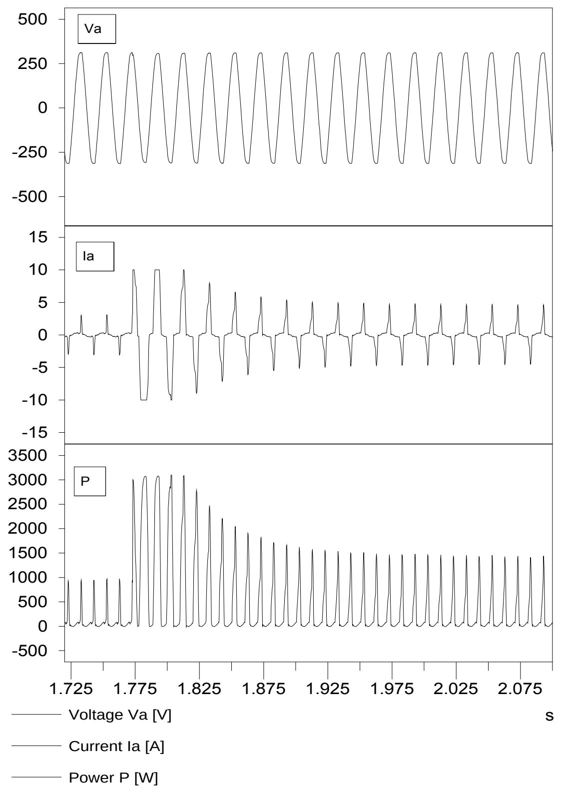

Fig. 6. The time characteristics of the supply voltage, the supply current and the active power of the Kawasaki robot at moving the JT2 axis

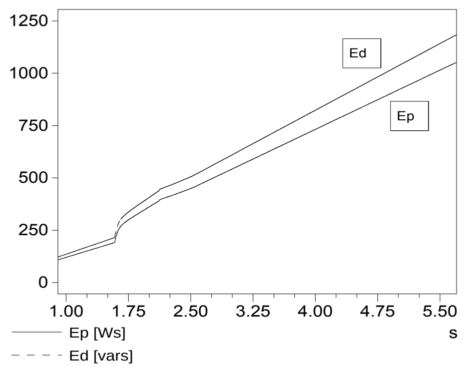

Fig. 7. The time characteristics of active energy and distortion reactive energy of the Kawasaki robot at moving the JT1 axis

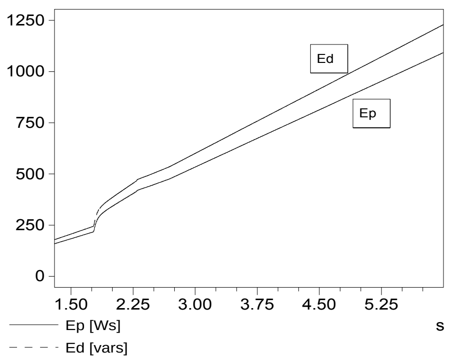

Fig. 8. The time characteristics of active energy and distortion reactive energy of the Kawasaki robot at moving the JT2 axis

Concluding remarks

The measurement study of voltage and current conducted on the robot Kawasaki indicates that there are considerable differences between currents received by motors working at various axes. This results from the construction of the robot manipulator, load torque of a particular axis and power of a particular motor. The different values of current received by motors at particular axes correspond to the amount of energy and power consumed by these motors. In consequence, it is possible to analyse energy consumption for a specific manipulator trajectory consisting of a sequence of movements realized by the particular axes.

It follows that it is possible to reduce total energy consumption by the robot by modifying the manipulator trajectory. Such a modification involves decreasing the range of angular motion for an axis with high energy consumption, simultaneously increasing the range of angular motion for an axis with lower energy consumption. Even though energy consumption is reduced by a relatively small value per one movement along the trajectory, when the movement is repeated several times, or several tens of times, the amount of energy saved becomes significant. In this way, modifying the robot manipulator trajectory for repeated movements, taking onto account the energy consumption at the particular axes contributes to cutting down the costs of the robot operation.

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