

MACHINE TOOLS ENERGY CONSUMPTION MEASUREMENT DEVICES

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Abstract – Measurement of energy consumption of machine tool is a fundamental step for improving the energy efficiency during production. Machine tool is a very complex product which need specific measuring devices for both types of energy usage during machining – electric and pneumatic. These devices, used in shop floor, should be robust and reliable. Several developed devices are presented to make a proper measurement of energy including PLC monitoring as a possible sensorless diagnostic.

Keywords: machine tool, measurement, ecodesign, energy

1. INTRODUCTION

Energy consumption during the use phase is the most negative environmental impact of modern machine tools, [1]. Together with increasing requirements for production cost reduction, strong research about energy efficiency during machining has been accelerated in last decade. Many instruments and devices are available on the market, however suitable set of measurement devices and corresponding methodology is still missing for such complex objects, as modern machine tool centers are. Especially for requirements regarding the range of current measurement from 0.1A up to 150A and sometimes even more. Set of measurement devices would be also useful to make a test according upcoming ISO standards, [2] and [3].

2. ENERGY MANAGEMENT OF MACHINE TOOL

Machine tool is a very complex construction, comprising many electric energy consumers with three types energy flows which need to be monitored, synchronously if possible, by different devices. These types are [4]:

- Auxiliary units – standard power supply based on 3-phase 50Hz AC. For example pump, fans, chillers etc.
- Inverters – DC line power supply with 600V and transform energy flow for machine servo motors
- Servo motors – supplied by 3-phase AC with PWM, which are motors for machine axes. Frequencies for power supply are usually 2,5-8,4 kHz.

Second type of energy, which cannot be neglected, is an energy of compressed air. It is widely used for cleaning scales, cleaning the spindle during changing the tool and for balancing vertical axis. Consumption of the compressed air

can reach up to 30% of the overall machine energy consumption.

Typical electrical circuit

Typical standard electric circuit of machine is shown in Fig.1, which is basically the same for all types of CNC machines. The machine can be virtually split into two main parts:

- Inverter controlled units – inverters and servodrives for moving axis and spindle to make a cutting process and machine the workpiece
- Auxiliary units – another energy consumers to support the cutting process like pumps, cooling devices, air-conditioning, lights, chip conveyor and many more. These units are an integral part of the machine and modern CNC machines cannot work properly without them.

Usually the standard CNC machine has only one main electric supply, going through the main switch, where the overall electric consumption can be monitored.

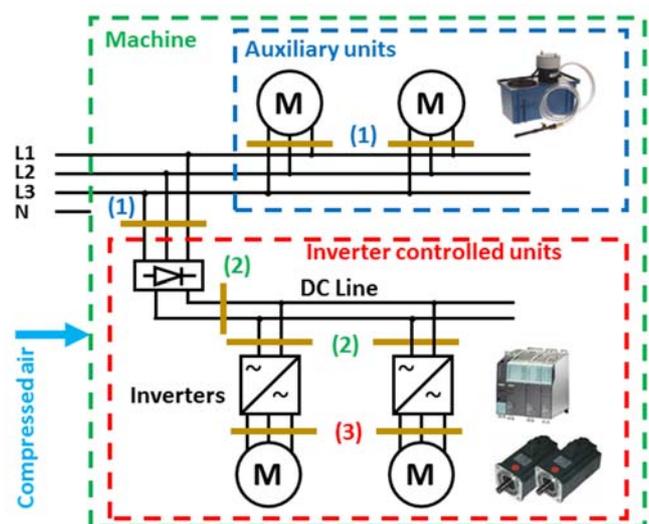


Fig. 1. Typical electric circuit of machine tool.

Compressed air consumption

Together with electric energy, the compressed air flow should be measured as well. Compressed air is produced by external compressor, which is usually used for several

machines or, typically, for the whole shop floor. Compressed air consumption is defined by an air flow, when pressure must be within tolerance, which is usually about 6 bar.

If only one machine tool is monitored from energy consumption point of view, the air flow energy should be recalculated to its electrical equivalent. Quite difficult, but very precise, equation can be used for this recalculation based on adiabatic change of gas.

Many measurements of machine tools and air compressors have been done with the results, that air consumption can be replaced by constant relationship between air flow and electrical equivalent, [5]. As a relevant relationship can be used (1):

$$l_{(6bar)} \frac{1}{\text{min}} \approx 30W \quad (1)$$

The error of calculation by using this formula is less than 1% which is accurate enough for calculation of energy consumption of machine tools.

Types of auxiliary units activity management

Different types of auxiliary units control management can be found in the machine. Typical main types of controlling are:

- Continuous operation – standard unit activated with machine switch on, for example inverter fan
- Intermittent operation and periodic switching – programmed operation, for example lubrication
- Intermittent operation and aperiodic initiation – typically pumps. This regime is based on NC program for machining the workpiece.

Intermittent operation can be periodic or aperiodic which is usually determined by PLC settings.

Graphical presentation of all presented activity managements is shown in Fig. 2.

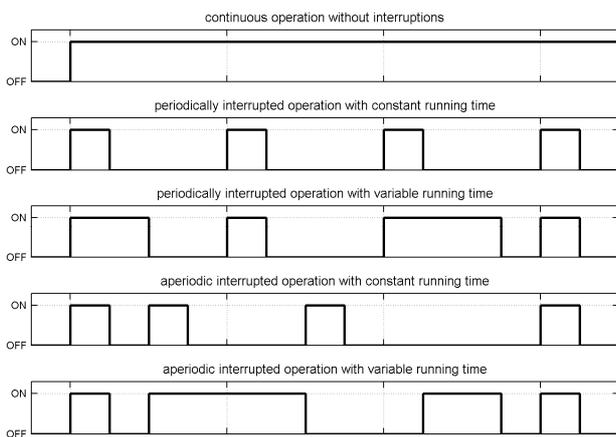


Fig. 2. Possible activity managements.

Some unit are controlled by machine control system, so their activity management is known and can't be measured in some cases. It can be predicted by analysis the NC program. However some units, like cabinet air condition, are controlled by independent variable (temperature), which is not predictable. These units have to be measured directly in all cases. The example of unpredicted operation management is

shown in Fig. 3 where different time gap between second initiation and others initiations is different.

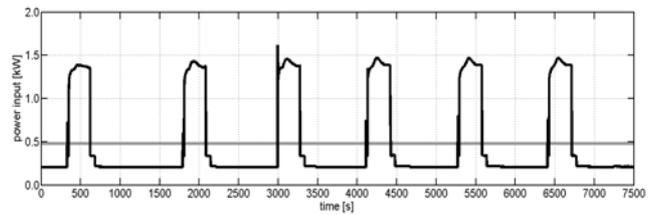


Fig. 3. Example of activity management of cabinet air conditioning

3. MEASUREMENT TIME FRAME

A big question is a time frame for measurement to receive requested results about energy management of tested machine. Several types of measurement can be realized.

Measurement for possible machine modification can be short, focused on specific machining regime and set-up. This consists of list of short tests to analyse behaviour of specific unit or its reaction to the impulse from machine control system. These tests are typical by higher sampling frequencies, short time of measurement and sometimes by saving raw data for further analysis. Usually transient states of units are monitored and analysed. Proposal of typical tests for machine tools is written in new international standard ISO/CD 14955-2, [2].

For economic aspects of machining on the level of whole shop floor or even the company, long-time frame of measurements are done. This means, that high sampling frequencies are used to collect data to the measuring device internal processing, but low frequencies for saving calculated data are set. This is for saving space on the storage, because huge amount of data are saved because the long-time frame of measurement. Summary plots and tables are a result of this type of measurement.

3. MEASUREMENT DEVICES

Presented possible options of measurement – time frame, sampling frequencies, types of energy flow etc. define relatively high requirements for measuring devices which can be used for machine tool complex analysis.

Typical range of input current is one of the biggest challenge for suitable measurement devices that has to be solved before starting the measurement. Modern machine tools are typical by high acceleration and deceleration of servodrives which means, that input current can rapidly change from very low level – about 0.2-0.5A (stand-by regime of motor) up to very high level (for large machines) – commonly more than 100A. Thus probes with proper range and low error has to be used, which is not sometimes easy.

Next step is to analyse the construction of the machine. Based on this analysis, required number of measuring channels is evaluated to be able to describe the energy distribution in the machine. A sufficient number of measuring channels is thus necessary. For typical modern machining centre, more than 4 time synchronous measuring channels are necessary for the 3-phase 50Hz AC power and 3 or more channels to cover the DC line for important servo drives. On the other hand, typically only one or two measuring point for

compressed air are enough to have an overview about air management.

Several developed devices to cover all energy consumption and energy flows inside the machine will be presented in next chapters.

3.1 Portable 3-phase 50Hz AC power analyzer

Typical production measuring devices for practical usage, not for laboratory, for 3-phase 50Hz AC power have up to four 3-phase channels (Norma 5000, Elcom ENA500) with time synchronization of all channels. Several patrol devices like Chauvin Arnoux C.A. 8335 or Fluke ScopeMeter with one channel can be used together, but there is no time synchronization, therefore combining data is very difficult and not easy to do it. Also the very high price for large multi-channel apparatus is also not welcomed by the machine tool producers, because such devices are usually designed for laboratories, not for shop floor usage.

Thus transportable low-cost multi-channel device (called KR2014-7) with high accuracy of measurement has been developed in cooperation with the KMB SYSTEMS company, specialized in designing electrical measuring devices. The KR2014-7 has 7 independent channels, where one channel is a time master and 6 channels are synchronized in time by the digital signal from the master. Data synchronization is therefore guaranteed. For machine tool analysis is important a mutual time synchronization of all channels in the device than observance the absolute time to be able to analyse energy distribution in one time point. If time synchronization with other measuring devices is required, KR2014-7 has a digital input for external signal 1PPM, switched 1x per minute with time duration 200ms. Synchronization is for leading edge. Signal can be passive or active 0V/24V.

Hardware of KR2014-7 is based on high accuracy power quality analyser ARTIQ144 which is used for all channels with very low time fluctuation and precise signal processing. Fundamental parameters for machine tool power measurement are in Table 1.

Table 1 KR2014-7 fundamental specification.

Power quality measurement	EN 61000-4-30, class A
Sampling frequency	12.8 kHz
Samples per period	256
Max. measured frequency	6400Hz
Digital filter	819.2kHz
Current measuring range	0.2 ÷ 150A
Current 3-phase channels	7
Voltage 3-phase channels	2
Current uncertainty	<0.1% from value
Voltage uncertainty	<0.1% from value
Time saving data period	0.2s, 1s, 2s, 5s, ...
Internal memory	512MB



Fig. 4. Multi-channel power analyser KR2014-7.

To have a possibility to measure wide range of input current with high accuracy for low and high level of current, split-core current transformers, type JC24F, are used. The advantage of these transformers is that they can be installed into the electrical cabinet without decoupling of electrical wires, which is always difficult and not welcomed operation. Important parameters of JC24F are in Table 2.

Table 2 Split-core current transformers

Current ratio	200A/66.6mA
Current range	÷200A
Linearity error	-1±1%
Phase Angle Error	+1.0±1°

This device is designed for short-time as well as long-time period measurement due to its firmware, which is performing all signal processing inside the firmware and only preconfigured values and parameters are saved into internal memory of each ARTIQ144 module. That is why KR2014-7 is able to measure continuously active power, at 7 points, more than 23 months with data saving period of 0.2s. Or active power plus current plus voltage up to 12 months with this saving period. This is far enough for analysing economic aspects of the production and machining efficiency of the observed machine. Data can be than downloaded into .CSV format or into Microsoft SQL database for further mathematical operations and reporting.

3.2 Modular low-cost 3-phase 50Hz AC industry measurement

In case of very complicated machine with a lot of units with autonomic behaviour and long-time period of measurement together with “no other device around the machine” requirements, another type of measuring device can be used. Device such this is usually installed inside of the electrical cabinet and using more precise current transducers. The big advantage of this system is its modularity, which is theoretically infinite and it is able to measure each energy consumer separately.

One of such system has been based on SMC144 measuring devices from KMB SYSTEMS. Each SMC144 device is independent device with its own RTC (real time

clock), therefore new device for time synchronization has been developed based on Raspberry Pi computer. This is called time synchronizer. Principle of working is downloading time from one chosen SMC144 module and comparing with the time of each other modules (Fig. 5). If the time shift is higher than configured limit, specific correction is being applied. To avoid the too big time shift after initiation of the whole system, time correction is done with several steps. Time is checked periodically each hour.

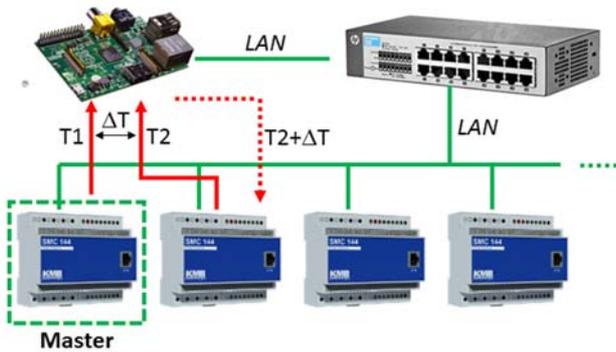


Fig. 5. Set of SMC144 modules with time synchronization.

Firmware of the SMC144 is also designed to make signal processing inside and save only configured parameters.

With this time synchronization, saving system and software similar to ARTIQ144 module, even such low-cost system is available to measure the machine tool precisely and for very long time period.

Typical installation of this modular system is shown in Fig. 6.

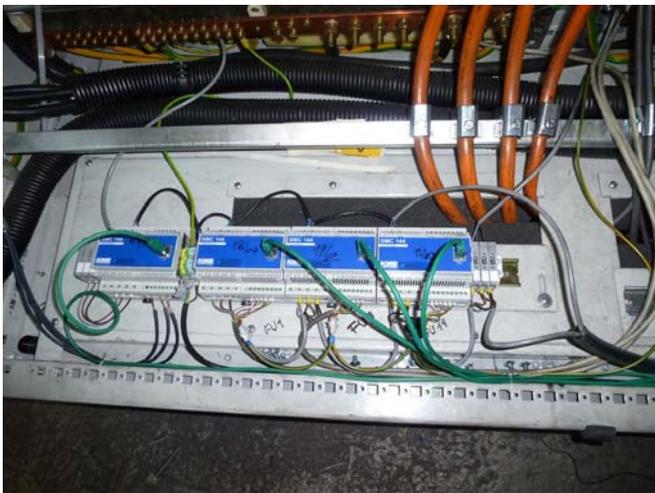


Fig. 6. Installation of low-cost modular system.

DC line measurement

The specific area of measurement is a servo drives part of the machine. This energy flow can be separated into two parts, as is shown in Fig 1. Measuring the energy between inverters and motors is very complicated due to limited access to cables and motors. Easier way is to measure the inverters input energy between rectifier and each inverter. This is called DC line. This signal can be measured for example by Hall probe, which is installed directly on the DC line wire (Fig. 7).



Fig. 7. Hall probes installed on frequency converters.

To analyse the signal, high requirements must be fulfilled by the device for signal processing. Especially for the machining process monitoring, where the current waveform of each tool tooth load is monitored. 50kHz sampling frequency is used for this test.

Therefore special measuring device - U12135 has been developed. Hardware of the device is based on National Instruments equipment with LabView based software. Main characteristics of the device is shown in Table 3.

Table 3. DC line measuring device (U12135).

Sampling frequency	50 kHz
Number of channels	8
Hall probe LA 55-P accuracy	0.65%
Hall probe LA 55-P time response	< 1 μ s

Comparison with the laboratory analyser NORMA 5000 with very precise current bypass has been realized to check the U12135 measurement capability. The construction of the device for DC line measurement is shown in Fig. 8.

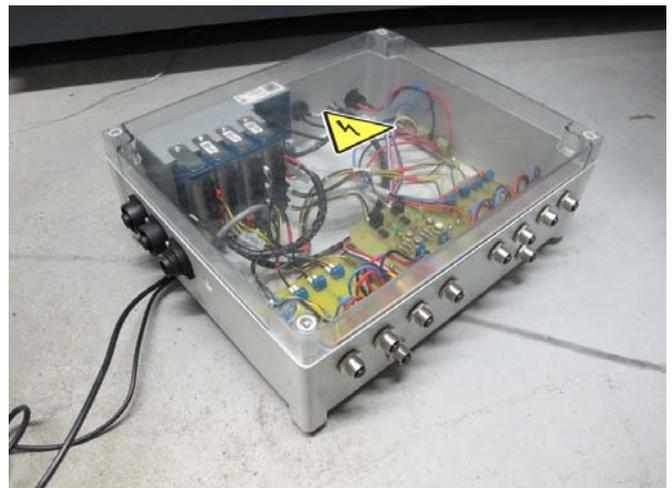


Fig. 8. Device for the DC line measurement.

3.3 Compressed air measurement

The second important type of energy, consumed by the machine tool, is compressed air. Compressed air is the most expensive type of energy, therefore its reduction brings significant cost saving. To measure the air consumption is not

a big problem because standard production systems are available on the market. For example from FESTO. After many tests, realized during last years, the result is, that air temperature and pressure is not so significant and can be neglected to have still accurate measurement comparing to the electric energy. However air flow is the main parameter and has to be monitored.

An integral part of the device are filters, because air, coming to the machine can be contaminated by dust and aerosols which are dangerous for the measuring sensors.

3.4. Special PLC and active power analyzer

An advanced analysis of the energy distribution and management of the machine can be done by PLC and machine regime monitoring, connected to the active power measurement. This analysis can be used both for units control and technology optimisation as well as for reverse analysis of units's consumption without their measurement. In future it can be used for sensorless monitoring based only on PLC activity. In Fig. 9 the scheme of the system is shown.

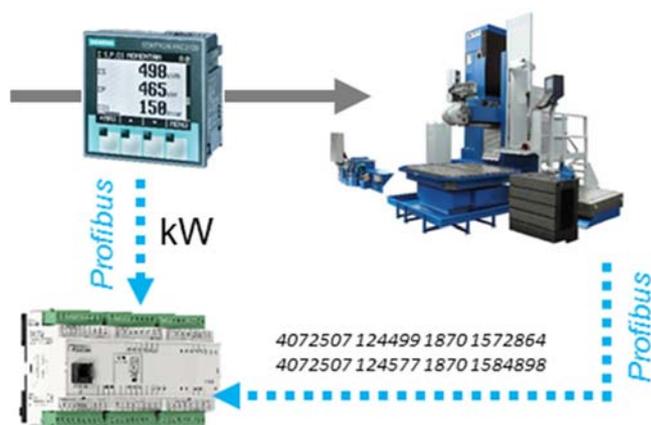


Fig. 9. Data communication of PLC analyzer.

This system combines monitoring of three important groups of parameters to have an overview about the machine status and energy consumption. These groups are:

- Machine production status – JOG, MDA, AUTO
- Energy consumers activities – auxiliary unit, controlled by PLC
- Overall machine energy consumption – installed usually on the main switch

The main advantage of this system is in signal communication where aperiodic signal processing is developed. To save the space in memory the system doesn't save data in fixed time interval. Special data structure is designed to save data only if any change is realized. In this case, the time and identification of the situation is saved. This procedure reduce significantly the required memory space and processing time of the machine control system as well. Also data flow of profibus communication is reduced.

Software procedures to analyse data and recalculation to the standard time axis is also developed. Therefore standard overview of machine activity and energy consumption is possible.

With this system, machine state and corresponding active power can be compound into one picture or database to have another important information about machine usage and energy consumption as is shown in Fig. 10.

One of the significant output of this analysis is also an overview about time usage of monitored components to predict service intervention and the life prediction which can save costs for unexpected crush situations.

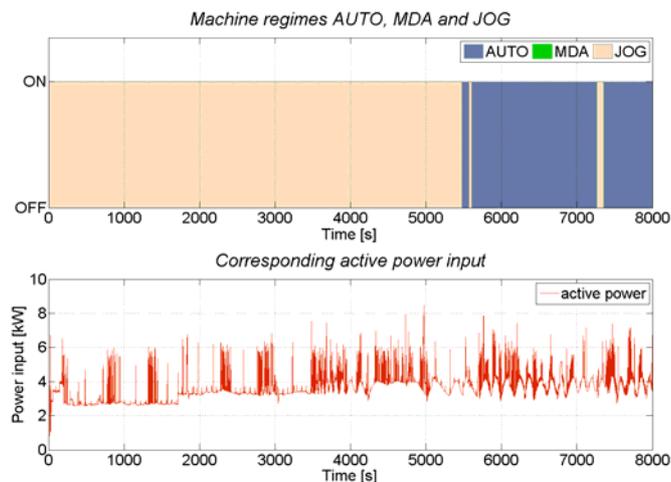


Fig. 10. One of possible outputs from PLC analyser.

5. CONCLUSION

Measurement of the energy consumption in machine tool industry is a complex task where 2 main energy types (electric and pneumatic) should be considered. Because both 3-phase AC and DC type of electric energy is used for machine parts supply, each of these need special measuring devices capable to make a right measurement and first data processing. Together with compressed air flow measurement, this set of devices covers the relevant energy input of the machine which consists of electric and pneumatic energy.

Several of possible measuring devices were presented including new devices designed especially for machine tool monitoring. These newly developed devices are transportable low-cost multi-channel device and modular low-cost device for 3-phase AC energy together with DC line measurement device and compressed air measurement. Special application of PLC monitoring has been presented as well.

These devices are designed for specific test for machine tool industry but can be used for other applications. Both short-time and long-time period tests can be realized to analyse the machine for requested results. It could be tests for machine modification and installed unit testing or measurement for economic evaluation of energy costs during long production time.

6. ACKNOWLEDGEMENT

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7. LITERATURE

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