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ELECTROMECHANICAL SYSTEM ANALYSES

Stanislav Gregora * — **Jaroslav Novák** ** — **Vladimír Schejbal** *

A measuring system for testing special AC electric drives has been created. The structure of a computer program for indirect determination of the induction motor torque using a mathematical model for real-time processing is presented. The possibilities of extension of the program for analyses of the AC motor power are given along with a program algorithm for power analyses. Moreover, the accomplishment possibilities of direct tensometer torque sensors are studied.

K e y w o r d s: AC machines, measurements, induction motors, DSP, sensors

1 INTRODUCTION

The measuring system for testing of special AC electric drives has been created at the Department of Electrical, Electronic and Safety Engineering (KEEZ) of Jan Perner Transport Faculty of the University of Pardubice [1]. Measurement can be performed for both steady and transient states. Computation algorithms have been designed considering the possibility that real-time processing of electric and non-electric variables can be performed. That means the balance between the higher accuracy and faster computations should be always kept. The measuring system consists of two parts. The first part contains a system of non-electric value sensors for direct measurements, the evaluation of that is performed using a storage oscilloscope or PC with an additional measuring card. The other part is microprocessor measurement and computing unit that measures the responses of electric and non-electric values. Using the responses, the unit performs real-time computations of other drive values. The measured and computed values are transmitted into PC.

The microprocessor measurement and computing unit is developed in cooperation with CTU Prague, Faculty of mechanical Engineering, Josef Božek Research Center. It is based on utilization of fast DSP. Except the central processing unit, the measuring unit contains interface circuits for connection of sensors of currents, voltages and revolutions. The hardware concept of the measuring unit is described in detail in [3].

Two versions of software for microprocessor measuring equipment have been debugged. The first version contains the solution of the model of the induction motor. Using this code, real-time complex analyses of the induction motor, especially torque computation, are done. The core procedure of the measuring unit for indirect determination of induction motor torques is the computation of the current model. The principles of the mathematical model and results have been described in detail in [2].

This paper presents the software structure for microprocessor measuring equipment for solution of a real-time mathematical model of the induction motor. Some properties of the model, which are connected with setting-up the accuracy of model parameters for torque computation, are briefly described.

The second software version serves for power analyses of electromechanical systems, especially for AC drives fed by inverters. The basic code functions, principles and computation structures are presented along with examples of concrete measurements performed at the laboratories of CTU Prague and of the University of Pardubice.

Moreover, the accomplishment possibilities of direct tensometer torque sensors are studied.

2 PROGRAM STRUCTURE FOR COMPUTATION OF CURRENT MODEL OF INDUCTION MOTOR

The inputs of the described program for real-time computation of the mathematical model for induction motor are mechanical revolutions scanned by an incremental sensor with 1024 pulses per revolution with direction resolution and two-phase currents of the machine stator. These values and all values computed at single steps of the algorithm are available and visible using PC. Particularly, the stator current components of rectangular coordinates α, β related to rotor magnetic flux components, stator current phasor modules (space vectors) and rotor magnetic flux values, instantaneous values of internal electromagnetic torque, mean values of internal electromagnetic torque, mechanical torque values computed by correction, stator current magnetized components, stator current torque components and mechanical outputs are considered. All described variables can be shown as

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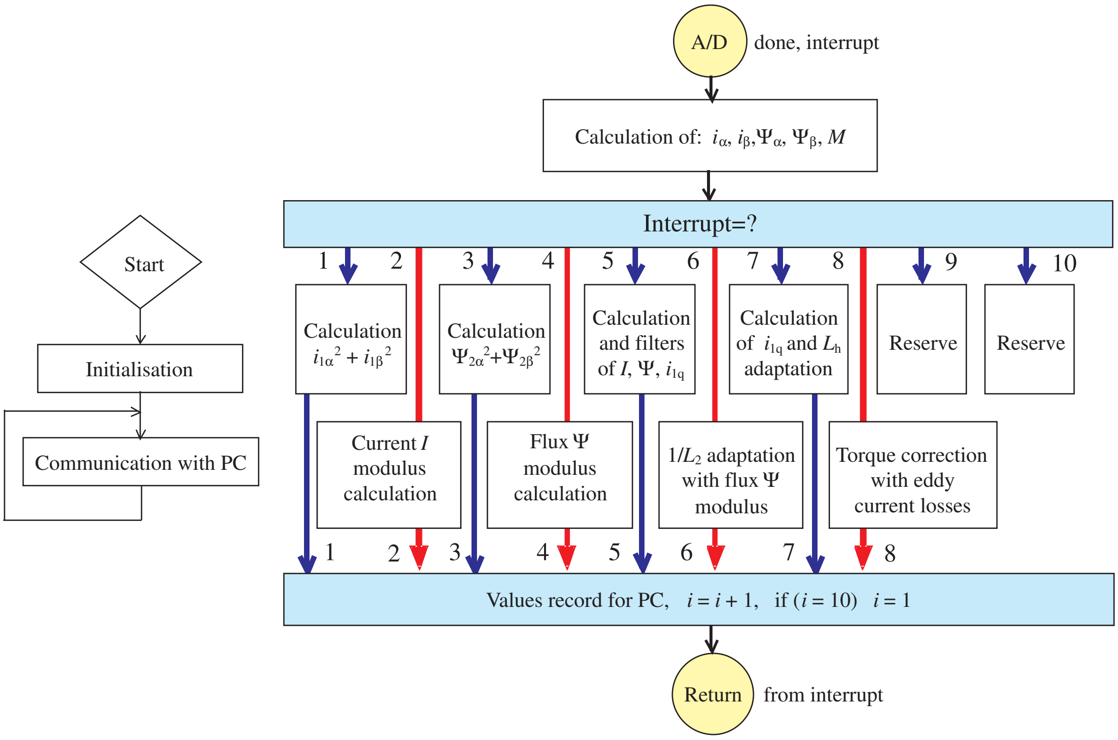

Fig. 1. Program algorithm for the mathematical model computation of the induction machine.

filtered or non-filtered. The stator current torque component I_{1q} is calculated using coordinates d, q of internal electromagnetic torque according to the following equation:

$$i_{1q} = \frac{2M}{3p_p\Psi_2} \tag{1}$$

where p_p is the number of machine pole pairs. The magnetic component of the stator current i_{1d} is calculated according to the following relationship:

$$i_{1d} = \frac{\Psi_2}{L_h} \tag{2}$$

The value of L_h is not constant and it is changed according to the position of the working point of machine magnetic characteristics. This non-linearity is respected in the program even if the stator current magnetic component is computed. The inductance L_h is adapted by three piecewise straight lines according to the magnetic flux.

The program for DSP processor TMS 320F240 is coded by the assembler language. The following concept of the whole program is used. After initialization, the event manager module of the processor periodically generates, with $100\,\mu$s period in connection with the timer state, the start of A/D conversion using two parallel built-in converters the inputs of which are fed by sensor signals of two machine phase currents. After conversion finishing, the interrupt is generated whose subroutine performs the computation of the mathematical model. For any such interrupt, *ie* , any $100\,\mu$s, new computations of the magnetic flux components, of the instantaneous value of the internal electromagnetic torque and filtering of the described variables are performed. The period length has a principal effect on the computation accuracy and it should be as short as possible. The evaluation of revolution using pulses sent by incremental sensor is done for every fiftieth interrupt, *ie* , every 5 ms.

The interrupts of A/D converters are arranged into groups of tens. For any interrupt out of the ten, some other variable is calculated, as some of these calculations are time consuming such as modulus calculations of currents and magnetic fluxes using the Pythagorean theorem. This calculation cannot be conducted every $100\,\mu$s, and simultaneously, the frequency of performing of these calculations does not influence the accuracy. It follows that α and β values of stator current components are recomputed every $100\,\mu$s the values of other variables are recomputed with 10-times longer period, *ie* , every 1 ms. Considering the fact that the program is coded using the assembler of processor with a fixed point, internal scales are used for all variables in the program.

Communication on the principal level of the whole program is done using the RS232 link with PC. The program algorithm can be clearly seen in Fig. 1.

3 TESTING OF PARAMETER EFFECTS FOR TORQUE COMPUTATIONS

After debugging the torque computation program, several trials have been performed to verify the effects of a correct setting of the main inductance L_h and rotor resistance R_2 on the accuracies of static torque computations. The data of the dynamometer balance have been

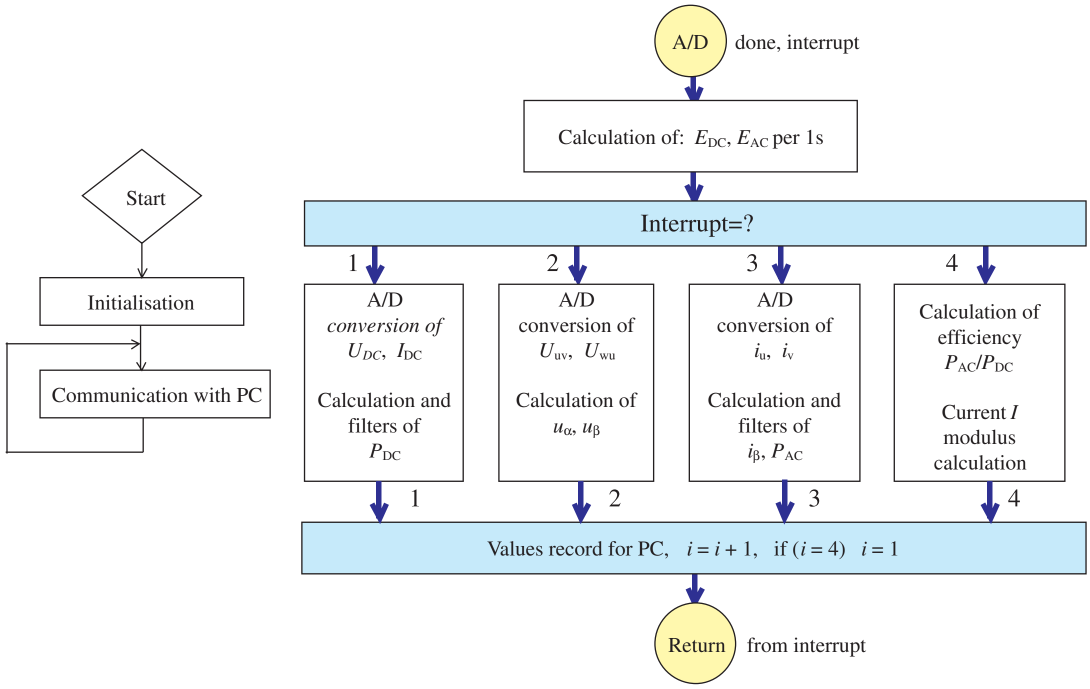

Fig. 2. Program algorithm for power analyses

considered as the correct values. The testing of inductance effects has been more complicated as inductance values are changed in dependence on the magnetic flux and this property is respected in the program by piecewise linearization.

The effect of rotor resistance R_2 value on the absolute error of torque calculation is approximately linear for the whole range of the tested torques from the open-circuit state up to the nominal torque. The effect of inductance L_h value is non-linear. For example, around 20 % increase of the model inductance, in interval of torques from open-circuit state up to approx. 30 % of its nominal value, produces the computation torque errors in the order of %. When the torques are further increased, the calculated torque data have slowly increased even now against the true torque on the electromotor shaft, however, the torque errors have reached values even more than 50 %. Greater errors have been observed for the generator mode.

4 SOFTWARE PRINCIPLES AND STRUCTURE FOR POWER ANALYSES OF ELECTROMECHANICAL SYSTEMS

The power-measuring program is intended for testing of drives with a three-phase motor fed by an inverter. The measuring equipment program evaluates electrical powers of the direct- and alternating-current sides of the converter. The program input values are samples of the direct voltage and current of the inverter input and samples of two phase-to-phase voltages and two phase currents of the inverter output.

The program performs real-time computation of instantaneous values for the DC power. Moreover, the program performs the calculation of the time integral of this direct-current power, *ie* , power consumption calculation. The DC power calculation presents no problem.

Using AC samples of two phase-to-phase voltages and two phase currents, the real-time instantaneous active power of the inverter output, filtered value of active power and time integral of active power are computed. Filtering of the active power is especially done considering enormous amplitude swings due to voltage pulse width modulation (PWM) of the inverter used as a three-phase power supply.

The key problem for program development has been the evaluation of the instantaneous value of active power. The first possibility would be to use the definition of the active power as the mean value of the load power per a period of the supply voltage. For a frequency controlled drive, the situation is very complicated due to changeable frequencies of the first harmonics of the supply voltages as it would be necessary to indicate and change the computation periods of the power mean values. Considering these changes the sample numbers for computation periods would be changed for a constant sample frequency and computations for various frequencies would not be equivalent. Even indication of the first voltage harmonic periods considering a non-sinusoidal supply would be very complicated.

The second possibility of real-time active power computations would be the computation of the products of RMS values of phase voltages, phase currents and power factors. Again, the RMS value computations create problems due to indication of computation periods. Moreover, it would be very difficult to determine the phase shifts of the first harmonics of voltages and currents in case the inverter is used as a power supply.

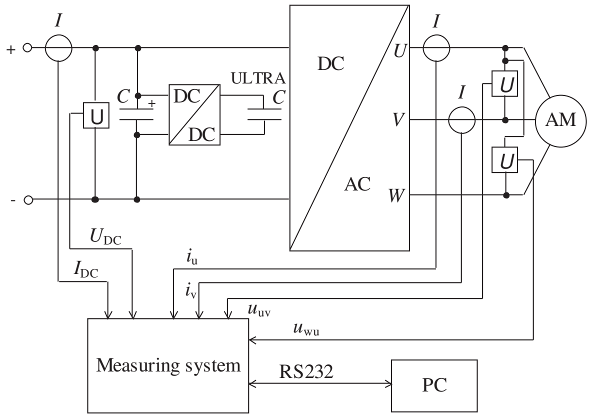

Fig. 3. Block diagram of measurement for a drive with an ultra-capacitor.

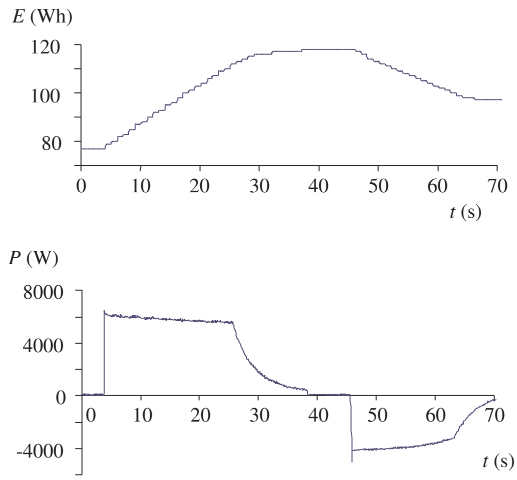

Fig. 4. Responses of energies and powers during charging and discharging of the ultra-capacitor.

Due to the above reasons the following procedure has been used. It is based on utilization of a transformed two-phase coordinate system of α and β. This does not ask for indications of the first harmonics of supply voltages. Moreover, it is not demanding arithmetically. It is very effective and speeds up the real-time applications. The whole active power of a symmetrical three-phase load for system of α and β is given by the following equation

$$P = \frac{3}{2}\,\mathrm{Re}\left[\hat{\mathbf{U}}\,\hat{\mathbf{I}}\right] = \frac{3}{2}(u_\alpha i_\alpha + u_\beta i_\beta)\,. \tag{3}$$

The voltage and current components of α and β are computed using the following simple transformation equations

$$\begin{aligned} i_\alpha &= i_u\,, & i_\beta &= \frac{i_u + 2i_v}{\sqrt{3}}\,, \\ u_u = u_\alpha &= \frac{u_{wu} - u_{uv}}{3}\,, & u_\beta &= \frac{u_{wu} + u_{uv}}{\sqrt{3}}\,. \end{aligned} \tag{4}$$

The next program outputs are time responses of AC active power to direct power ratios, *ie*, the inverter efficiency responses.

The program algorithm is performed using operating interrupt subroutines derived from A/D conversion ends. The used processor possesses two A/D converters connected in parallel and therefore new samples of two variables are available at the beginning of every interrupt. Interrupt servicing is performed using four subroutines that are cyclically repeated. These four subroutines sequentially perform the whole above program. A/D conversions creating sequentially interrupt generations are started with $125\,\mu$s periods, *ie*, the whole algorithm is performed using four subroutines during 0.5 ms periods. Therefore, program output variable values are renewed after this period. The values of time power integrals of E_{DC} and E_{AC} for DC and AC sides are only renewed with 1 ms periods. The program structure is shown in Fig. 2. It clearly shows that for individual interrupt subroutines the input currents and voltages are sequentially measured and partial computations are performed. The fourth subroutine does not perform A/D conversion. Efficiency and AC modulus are only computed using α and β components and Pythagorean theorem.

5 APPLICATION OF SYSTEM FOR DRIVE POWER MEASUREMENT

The system for power ratio measurements has been used for the measurement of powers for a drive with an ultra-capacitor. The measurement equipment connection to the drive can be clearly seen in Fig. 3. The DC current and voltage at the system input have been sampled. The whole system has been supplied with a dynamo during tests. Two measurement series have been performed. The first measurement series has been pointed at efficiency analyses of charging and discharging of the ultra-capacitor through a built-in DC/DC converter. The ultra-capacitor has been charged by the dynamo and discharged to the dynamo for various modes and simultaneously the difference between the energy E_{DC} delivered to the ultra-capacitor and delivered back to the dynamo has been analyzed. The real-time measuring equipment has calculated the power of DC supply circuit P_{DC} and the time integral E_{DC} The response examples of these measurements are shown in Fig. 4.

The powers of the drive whose inverter has been supplied by the dynamo and which has supplied a 3 kW induction motor have been analyzed in the second measurement series. In this case, the values of power and the time integrals for DC and AC sides of the inverter have been computed. The response examples of these measurements are shown in Fig. 5.

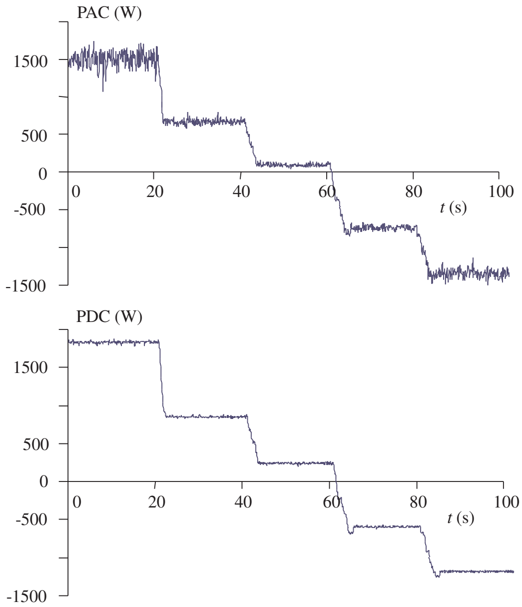

Fig. 5. Power responses for AC and DC sides of the inverter.

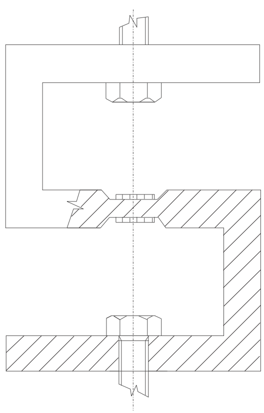

Fig. 6. Scanning element design with greater sensitivity.

6 TORQUE DETERMINATION USING TENSOMETER SENSORS

The methods and means for direct scanning of the dynamical torque are simultaneously examined at the department. It has been proved that for scanning of dynamical forces, the material deformation method can be considered. Due to demands, deformation of silicon elements, which possess better properties than metal sensors for this purpose, is used. Several variants of mechanisms for direct torque scanning have been done.

The last research variant is the torque scanning using force reactions of motor support points. Scanning silicon deformation elements are stuck into support points. This variant does not require additional motor construction design. Theoretical and experimental analyses have demonstrated that the variant with 4 support points is statically undetermined and inaccurate. Therefore this solution has been changed into a three-point system and, simultaneously, the third point in the motor axis should possess a degree of freedom (bearing). That has caused that the possible additional deformations have been removed and results have been more accurate. To achieve greater sensitivity, the scanning elements have been designed according to Fig. 6. The design possesses appropriate deformation (the relative deformation about $\varepsilon = 5 \times 10^{-4}$ should be reached for required sensitivity). The relevant deformation is transformed into resistance change

$$\frac{\Delta R}{R} = K \cdot \varepsilon \tag{6}$$

which can be evaluated.

7 CONCLUSIONS

The test equipment with a program for power analyses, with a program for the mathematical model of an induction motor and tensometer torque sensors are used for research and teaching purposes. Currently, a program combining the functions of both program versions is under preparation. This new program allows to do the energy transformation balance from DC side of inverter up to the mechanical part.

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