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Development of AC Slip-Ring Motor Based Advanced Crane Industrial Controller

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Professional paper

In situation where old crane drive with AC slip-ring motor has to be revitalized, or new drive with advanced controller designed, industrial crane controller (ASTAT®) is offered on the market as acceptable and low cost solution. Speed controller for AC slip-ring motor is developed as modular system capable to deal with all control, communication, protection and other specific industrial demands. Multiprocessor system is realized with microcontroller MC68332 (application program running), two SAB 82532 microcontrollers (distributing control system), two MC68302 (process I/O communication) and two DSP ADMC300 (speed and electromagnetic torque estimation).

Request from unavoidable industrial automation in complex industrial systems resulted in use of a smart components for every specific function in the frame of complex industrial task. In this paper the basic hardware and software platform for proposed controller is presented as well as the development software tools. Special attention is paid to additional speed and torque estimation modules designed and realized on different software and hardware platform regarding the core of the control system.

Key words: development, AC slip-ring motor, crane drive, industrial controller, revitalization

1 INTRODUCTION

In the last fifty-sixty years AC slip-ring motors are widely used in a many industrial tasks, such as material handling systems, pipe and paper mills, steel and rolling mills, container loading/unloading cranes, power plants, engineering workshops, etc. In the beginning, this control is focused mainly on the rotor motor side using speed based rotor contactor switching for discontinuous additional external rotor resistor change. Thanks to that, it was surely unique electrical AC machines capable to start with maximal available torque and at the same time drawing minimal stator current from the mains. In those years it was very pragmatic solution to use AC slip-ring motors for those tasks, because of its high robustness and very simple and effective speed/torque control from the rotor side. Emerging power electronics switches, especially thyristors, and putting the AC/AC converter in the stator side, AC slip-ring motors have got a new perspective in control domain. Although basic control theory claims that only phase thyristor control method from stator side is very pure (limiting control region app. 10 to 30 % about rated speed) combination with resistor control from rotor side results in outstanding features. With appropriate external rotor resistors switching and stable phase control of the stator voltage, all working points inside rated speed and torque quantities of 4-Q operation can be reached. Swedish company ASEA developed in 1970's analogue ASTAT controller especially intended for the material handling crane purposes, [1, 2]. It was designed for heavy duty installations, with static components required less space than a comparable relay based systems for the same purposes and with tachogenerator connection for speed control loop. Voltage and current ratings were from 3×220 – 3×500 V and 18 A – 1700 A. All the control electronics was in modular exchangeable circuit boards and the system was proven in more than 6 000 installations. Controller has all needed function for crane control but suffered of the lack of the flexibility (controller parameters change), pure communication and monitoring capabilities, and in some situation problems with components sensitivity due to the hard environmental conditions (temperature, dust, humidity). After that, Siemens made SIMOTRAS HD crane controller with voltage and current ratings from 3×220 – 3×500 V and 60 A – 900 A, [3]. Practically, it was with identical functions as ASTAT®, but built in a new technology, on the same platform as SIMOVERT Masterdrives and SIMOREG DC MASTER for DC drives. It uses tachogenerator and impulse encoder as speed feedback devices and communication with controller is realized throe PROFIBUS-DP. As a user interface it is possible to use operational panel OP1S or PC-program SIMOVIS. Comparing with old analogue ASTAT version, the advantage is in more flexibility in user interface and in communication with other devices in complex automation process.

The age of digital technique gives completely new dimensions in crane control possibilities. Request from unavoidable industrial automation in complex industrial systems resulted in use of a smart components for every specific function in the frame of complex industrial task. Considering crane problematic, the requests are very large. With new age crane controller, crane has to be seen as an open control system from outside. Recognising that, some OEM suppliers developed new generation of crane controllers based on wide spread AC slip--ring motors, intended not only for new drives, than for revitalization (revamping) of old drives too. Swedish company ABB together with Faculty of Electrical Engineering and Computing, University of Zagreb (Croatia) in the last 1990's developed new digital ASTAT® crane controller. Today, this is the most advanced controller in the field of crane control with AC slip-ring motors, especially in revitalisation tasks where the speed control in many cases has to be performed without mechanical speed sensor. The first installed digital ASTAT® controller was in EOT hoist crane in Husum paper mill in (Sweden) in 1999. Some other applications show diversity of functions supported by this controller. For example, 16 t and 170 t hoist crane in nuclear plant Forshmark (Sweden); 5 winch coordinated drive for power fleet mining mooring system with 80 kW motors (Bangka, Indonesia); electrical shaft in steel factory Avesta (Sweden); 2 EOT (Electrical Overhead Travelling) ladle crane; 3 planetary gearbox drive for 450 t/80 t (1.4 MW) ladle hoist in Baoshan steel making plant (China), etc. In this paper the development tools and hardware and software platform are described in more details.

2 OVERALL CRANE CONTROL WITH ASTAT CONTROLLER

Purpose of revitalisation is not only to extend the life time of electrical equipment, than also to include existing control system with new equipment on the global trend towards information systems which view cranes as critical components in some crane application, e.g. material handling systems, container loading/uploading etc. Typical crane automation structure with AC slip-ring motor controllers and complete information structure is presented in Figure 1.

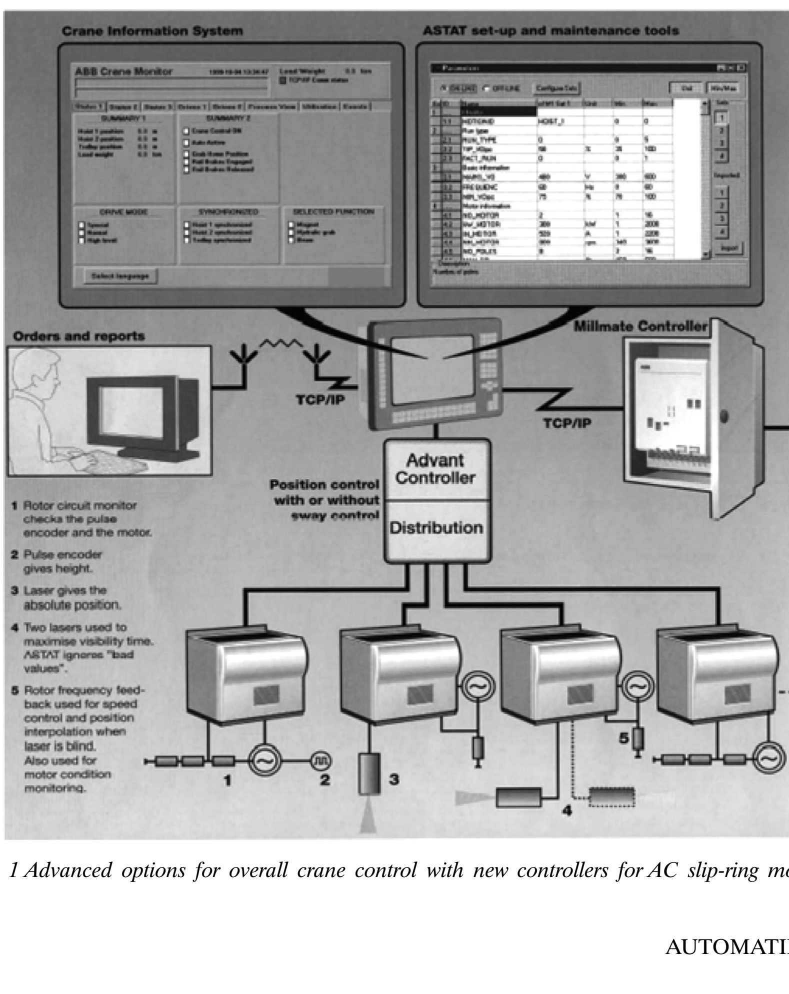

Fig. 1 Advanced options for overall crane control with new controllers for AC slip-ring motors

The crane's logistic information system is being more and more used for production cranes. The overriding level has to know precisely where materials (or cranes) are located and to perform all operations quickly, consistently and reliably. It is used for production orders, for crane condition monitoring as well as for set-up of crane motion controllers. Request on new advanced crane controller (revamped or new) to communicate with an existing o new plant management system must be fulfilled.

3 STRUCTURE OF THE CONTROLLER

The structure of the controller is presented in Figure 2. The frequency of the rotor voltage is determined by advanced digital filtering. By using the line frequency as a reference, the fundamental component of the rotor frequency gives the slip of the motor, which gives the speed in digital form. Controller uses the slip-ring motor as a virtual integrated pulse transmitter. A digital signal processor (DSP) is used for the frequency (speed) estimation, block A, Figure 2.

Electromagnetic torque calculation is based on stator currents and voltages. Calculated value is used as actual torque value for torque control mode and for automatic rotor resistors switching logic. For actual speed detection in oversynchronous regenerative mode of operation for sensorless drives (no mechanical speed feedback), sign of torque is used, block B, Figure 2.

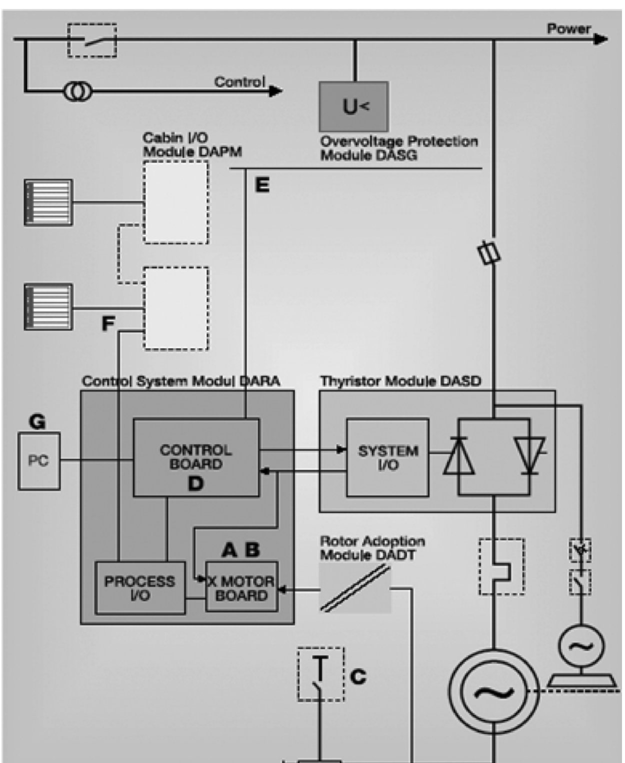

Fig. 2 Structure of the advanced crane controller

The switching algorithm execution of the rotor contactor logic is very fast. It minimizes the stator current of the motor, taking into consideration the momentary line voltage, required torque and resistors value tolerance. In each sampling time at the momentary motor speed, algorithm calculates maximal torque produced for each rotor resistor and choose resistor which gives the maximal developed torque. Using this algorithm, the start up adjustment is reduced, the motor can be used with a less stable line supply and it is easier to use existing resistors when revamping, block C, Figure 2.

The current and torque regulator has a response time of 3.3 ms similar to DC-drive. The torque reversal time is limited to 10 ms which is quite sufficient for cranes and similar motions but on the »safe« side to prevent hazardous control situations. The motor control programs are located in the control system module. All control system communication connections are made by optical fiber, block D, Figure 2.

Controller is designed to be an intelligent component in crane automation and information systems. Except process I/O optical link, there are also optical communication links for Overriding Control, Motion Control and Master/Follower communication interface, block E, Figure 1.

With remote I/O module in driver's cabin it is possible to operate with crane using potentiometer or stepped master switch device. Today, low cost plastic fibre can be used for distances of at least 27 m or HCS (Hard Clad Sylica) up to 1000 m. For low budget installations the master switch can be connected directly to the Process I/O of the Control System Module, and no Cabin I/O Module is required. Shared motion control is possible too, block F, Figure 2.

Commissioning and Maintenance Tool (CMT) is PC based program for crane controller and offers the following functions: monitoring and recording of reference and actual values; setting, changing, saving, uploading, downloading and restoring of parameters; remote application running from PC, block G, Figure 2.

4 CONTROL STRATEGY

Speed control systems for crane and heavy duty material handling purposes are well established systems using AC/AC phase angle controlled thyristor

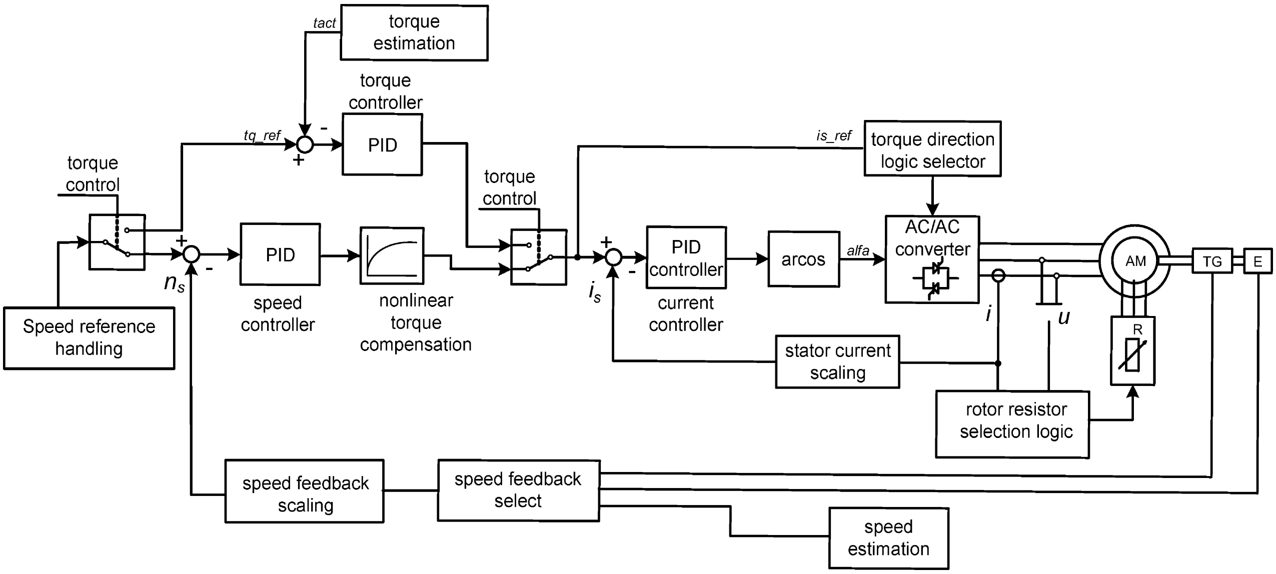

Fig. 3 Speed control loop in advanced ASTAT crane controller

converters, [4–8]. The crane controller performs stator and rotor control functions. By means of a pair of thyristors in each phase, stator voltage can be continuously controlled. Using five thyristor pairs (three pairs in each phase and two pairs for reversing) four quadrant operation is realized. Because the available motor torque of induction motor is proportional for each speed to the square of the stator voltage, the speed control is obtained by varying the stator voltage so that the desired speed is obtained for a given load. Rotor control gives to the motor the right characteristics optimizing the external rotor resistance. When lowering with a slightly higher speed than the motors synchronous (potential load), the motor will regenerate the energy back to the line in the most robust manner. This region of operation is often used when lowering a load in hoist drive, because reverse current braking, as another solution, lowering close to synchronous speed would result in slip close to two, and consequently overheating a rotor resistors.

Speed control loop with inner torque (current) control loop is presented in Figure 3.

Controllers are generally PID type, with parameters and structure dependent on the specific applications. Control program is running on the control board, controller parameters settings, program downloading, monitoring and data recording are performed on the PC. It is possible to use mechanical speed feedback sensors (tachogenerator and incremental encoder) as well as speed estimator based on rotor voltage frequency estimation.

5 HARDWARE/SOFTWARE PLATFORM FOR CONTROLLER DEVELOPMENT

Application program is running on the control system board, built up around the Motorola MC68332 microcontroller unit and supported by local operating system, Figure 4. This board is described in detail in [8]. The control board comprises a number of connectors interfacing other boards and devices. The CPU module configuration registers allows the user to configure and monitor system requirements. The system is set up by local operating system software after a power on reset.

Development system is supported with all software tools for programming, debugging and compiling, where application program can be developed in graphical, user-friendly environment.

5.1 Development tools for speed and electromagnetic torque estimation

In revamping old AC drives (when new controller should replace only old AC slip-ring control equipment, without motor, mechanical interface and rotor resistors), there is very often the lack of the space for mechanical sensor connection. In that situation, speed feedback control loop need estimated speed to fulfill control tasks. It is very often situation when the controller's sale is conditioned by the customer with possibility of sensorless drive, so financially aspect is emphasized a lot.

For speed and electromagnetic torque estimation, different hardware and software platform is used in

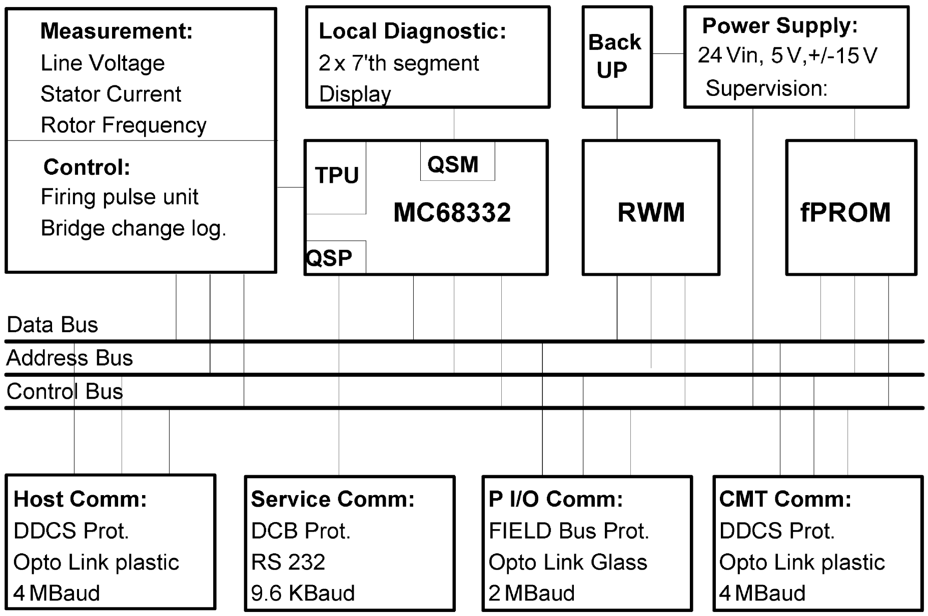

Fig. 4 Main control board as the core of the control system

the comparation with application hardware and software development. Complete hardware with two DSP ADMC300 board as a core of the estimation system is developed and designed, Figure 5 and 6.

As one can see on the Figure 6, speed and torque estimation unit is a module, which output signals are seen from main control board as other process signals. It is connected to process I/O unit via communication link RS422 (1–4Mbs). This module is offered on the market as optional unit, and activated in application program by parameter. In main application program it is seen just as one graphical symbol.

Speed estimation is based on (1) and (2), which means that the frequencies of filtered rotor voltages have to be measured, [6]. Signal processing in a frequency estimation block consists of analogue filtering, A/D conversion and digital filtering, Figure 5. Zero rotor voltage crossing is determined by a positive derivation block which produces impulses for time counter. If parameter TIME_U0 represent number of samples (pulses) between two consecutive zero rotor voltage crossing of U rotor

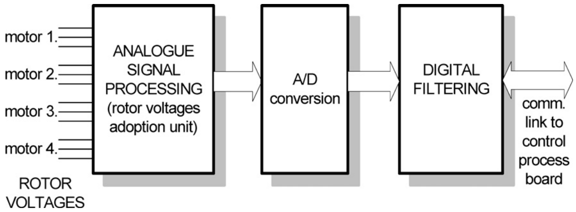

Fig. 5 Block structure of rotor voltage frequency estimation (RVFE)

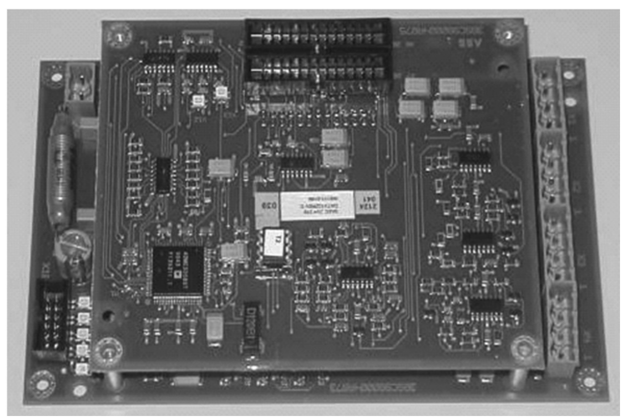

Fig. 6 Designed »sandwich structure« DSP board system for speed and torque estimation

phase, and respectively TIME_V0 and TIME_W0 from V and W rotor phase, then frequency of the rotor voltage is calculated according the equation

$$f_{rotor} = \frac{3 \cdot f_{sample}}{TIME\_U0 + TIME\_V0 + TIME\_W0}, \quad (1)$$

where f_{sample} is sampling frequency. After rotor voltage frequency calculation, actual motor speed is calculated using equation

$$n_{motor} = \frac{sign(tq) \cdot 60 \cdot (f_{stator} - sign(sl) \cdot f_{rotor})}{p}. \quad (2)$$

where n_{motor} is speed of motor in [rpm]; f_{stator} is frequency of stator and f_{rotor} frequency of rotor

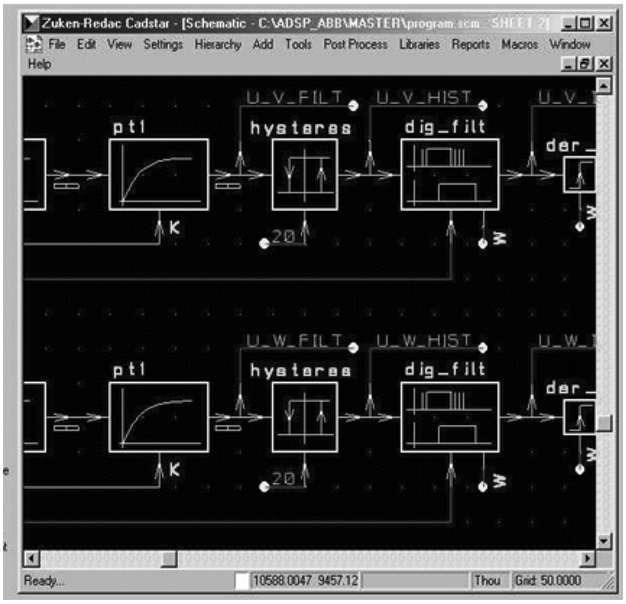

Fig. 7 Part of the graphical code realized in CADSTAR

voltage in [Hz]; p is number of motor poles; *sign*(tq) is sign of torque (forward torque direction »+«) and *sign*(sl) is the sign of slip (oversynchronous speed »–«). Realization of the above algorithm is realized on the development platform for ADMC300 DSP. The basic parts of development tools are graphical user friendly CADSTAR tool for code creation (Figure 7) and PARNAD tool for data acquisition, measurement and monitoring the system after program downloading, Figure 8.

Complete control system is tested with estimated speed as actual value for speed controller. For specific regime of operation where the rotor voltage frequency is low (e.g. speed close to synchronous) and where the rotor voltage amplitude is small (e.g. small load), accuracy of estimated speed is small. For those regimes, special nonlinear control with supervision of the critical variables is realized.

Electromagnetic torque estimation is based on the simple expression

$$T_e = \frac{2}{3} \cdot p \cdot (\vec{\psi}_s \times \vec{i}_s) = \frac{2}{3} \cdot p \cdot (\psi_{s\alpha} \cdot i_{s\beta} - \psi_{s\beta} \cdot i_{s\alpha}), \quad (3)$$

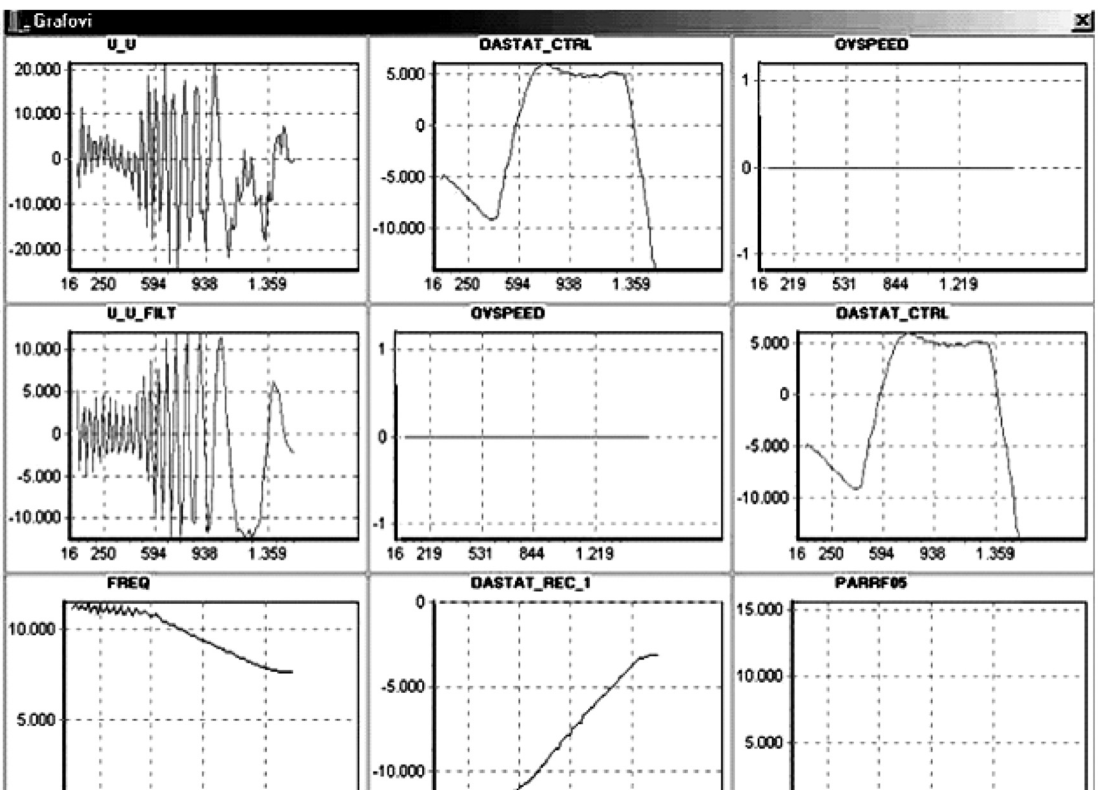

Fig. 8 PARNAD tool for data acquisition, measurement and monitoring

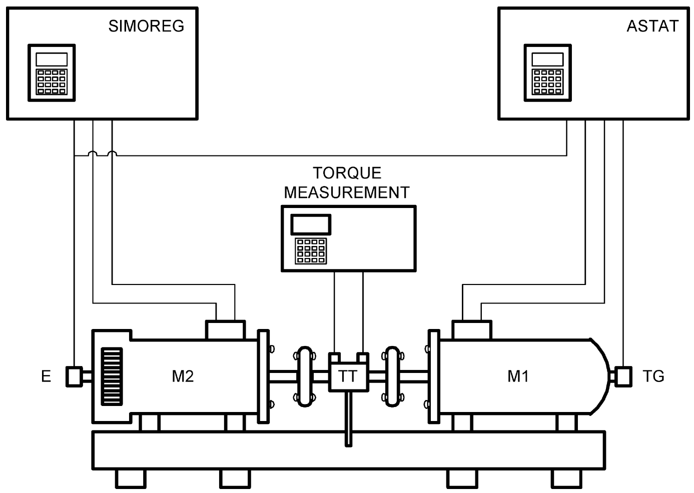

Fig. 9 Test bench for experimental verification of speed and torque estimation algorithms. M1: slip-ring AC motor: 3 × 380 V, 38.5 A, 18.5 kW, n = 1480 rpm, M2: DC motor, 220 V, 91 A, 17 kW, n = 1500 rpm

where stator flux components are calculated as

$$\psi_{s\alpha} = \int (u_{s\alpha} - R_s \cdot i_{s\alpha}) \mathrm{d}t$$
$$\psi_{s\beta} = \int (u_{s\beta} - R_s \cdot i_{s\beta}) \mathrm{d}t, \tag{4}$$

and stator voltages and currents are expressed in α-β coordinate system, [7]. Block structure for torque estimation is practically the same as for the speed estimation in Figure 5; only differences are stator voltages and currents as inputs in analogue processing block. The speed and torque estimation unit is experimentally evaluated on the laboratory test bench (Figure 9), and result of 4-Q drive test is shown in Figure 10.

6 CONCLUSION

Digital industrial speed controller for AC slip-ring motor is developed as modular system capable to deal with all control, communication, protection and other specific industrial demands. Especially for the purpose of revitalization of old AC slip-ring motor drives, speed and electromagnetic torque estimation, as separate module, is realized. Development of software/hardware support for main application and for speed and torque estimation unit are realized on the different development systems, one on microcontroller Motorola 68332 and second on DSP ADSP300. This emphasizes systems modularity and flexibility not only in development system and design, than also in real, toughest industrial environmental application. This is confirmed on the laboratory test bench and in close to 1500 installed industrial applications, especially in crane and another heavy duty material handling systems.

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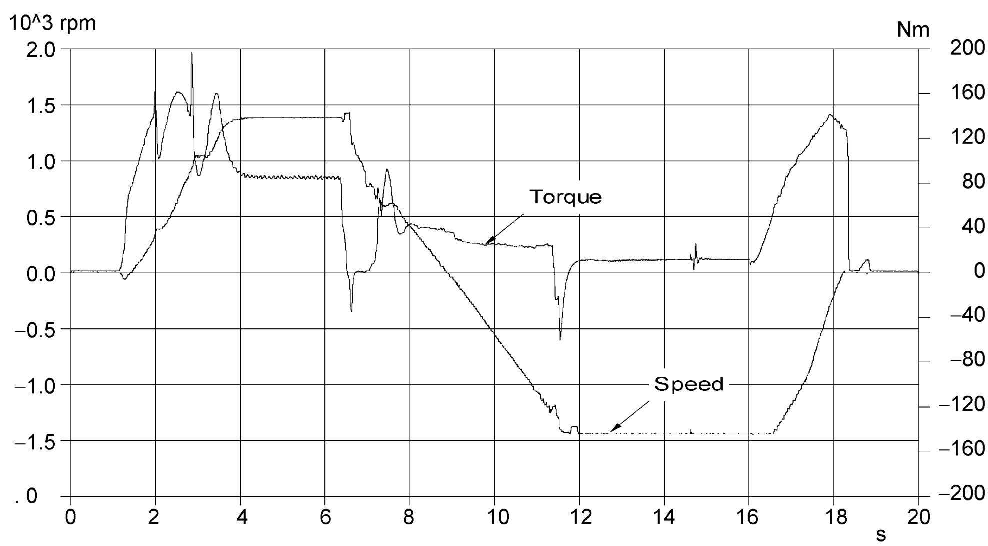

Fig. 10 Testing RVFE algorithm in four quadrant operation with potential load (typical hoist drive in crane applications)

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Razvoj suvremenog industrijskog regulatora za kranske pogone s asinkronim kolutnim motorom. Prikazano je suvremeno rješenje industrijskog regulatora (ASTAT®) koje se na tržištu pojavljuje kao kvalitetno i ekonomski prihvatljivo rješenje upravljanja kako pri projektiranju novih kranskih pogona s kolutnim asinkronim motorom, tako i pri revitalizaciji postojećih sustava. Sustav regulcije brzine kranskih pogona je izveden u modularnoj formi i s integriranim upravljačkim, komunikacijskim, zaštitnim i specifičnim, pogonom određenim, funkcijama. Radi se o multiprocesorskom sustavu s mikrokontrolerom MC 68332 (aplikacijski program), dva SAB82532 kontrolera (komunikacijske zadaće u okviru raspodijeljenog sustava upravljanja), dva mikrokontrolera MC68302 (procesna U/I komunikacija) te dva DSP-a ADMC300 (estimacija brzine vrtnje i elektromagnetskog momenta motora). Zahtjevi za neizbježnom automatizacijom kompleksnih industrijskih sustava, rezultirao je korištenjem suvremenih komponenata za svaku specifičnu funkciju realiziranu u okviru određene industrijske primjene. U članku je opisana sklopovska i programska podrška za predloženi industrijski regulator, kao i razvojna podrška i alati korišteni u sintezi regulatora. Posebna pažnja je posvećena realiziranim jedinicama za estimaciju elektromagnetskog momenta i brzine vrtnje motora, pri čemu su potonji realizirani na potpuno drugačijoj sklopovsko-programskoj podršci u odnosu na ostali dio (jezgro) sustava.

Ključne riječi: razvoj, asinkroni kolutni motor, kranski pogon, industrijski regulator, revitalizacija

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