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AUTOMATIC ON-LINE OPTIMIZATION OF AC WOUND MOTOR'S ROTOR RESISTORS IN ADVANCED INDUSTRIAL CRANE CONTROLLER

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Abstract. Digital integrated industrial controller is a specially designed speed control system for the cranes and another heavy duty material handling systems. It is intended for wound (slip-ring) motors and fully supports stator voltage control, rotor step switching, positioning, brake control and another application functions. Basically, the controller performs stator and rotor control functions. Stator control is related to the stator voltage control (motor torque control), using phase controlled AC/AC converter. The rotor control includes rotor resistor optimization logic, which changes the amount of the external added resistors in the rotor circuit by means of the rotor contactors. In this paper special attention is paid to the automatic rotor resistor optimization logic, realized in the crane application program in separate software module. All the application functions are running on the MC68332 microcontroller. Using process I/O digital outputs, main control board directly drive rotor contactors which optimize rotor additional resistors. The control system also includes protective functions, necessary for crane motor drives application.

Keywords: AC/AC converters, Industrial applications, Speed control, Torque control, AC wound machine, rotor resistors switching

1. INTRODUCTION

Of the drive systems suitable for the size between 20-1000 kW, the stator voltage controlled systems with wound motors (including rotor resistor control) since long time has been and still is very suitable solution. There are a lot industrial applications based on the system mentioned, such as material handling systems, pipe and paper mills, steel and rolling mills, container loading/unloading cranes, power plants, engineering workshops, etc. For the crane drive that most of its time is run in full speed up or full speed down, the losses except motors and cables are about 4% of the motor power. The figure is similar to the described stator voltage controlled system for wound motors and a regenerative frequency inverter drive system as well as a regenerative DC-drive system, [1]. However, the stator voltage controlled system has the important feature that the mayor part of the losses occurs in an external resistor(s), not inside the electrical equipment. Also, the regeneration of the full speed lowering energy is based on direct connection by fully conducting phase control thyristors of the over-synchronously running motor to the mains. In this mode, with a slightly higher speed then the motors synchronous, the motor will regenerate the energy back to the line in the most robust manner. When the lowering speed is approaching the synchronous, the rotor resistor is minimized and the direction of torque changes electronically. The new integrated drive controller minimizes the stator current and sensitivity to line voltage fluctuations considering the required torque, [2-5].
The controller with wound motor is more robust for the instantaneous quality of the line voltage than another type of the AC or DC drive. Of this reason it has been meaningful to design the advanced integrated controller capable to perform desired tasks at a line voltage as low as 75% of the nominal voltage
In this paper a special attention will be paid to the automatic rotor resistor optimization logic. By means of the rotor contactors, this logic uses special automatic procedure to choose the optimal motor characteristic, taking into account maximal motor torque and stator current limit, rotor resistor heating, supply voltage and number of resistor steps. The optimization of the rotor resistance, changing the additional (external) added resistors, is realized in a fully automatic way giving to the motor the right characteristics.

2. CONTROLLER STRUCTURE

Speed control systems for crane and heavy duty material handling purposes are well established systems using AC/AC phase angle controlled thyristor converters, [2-5]. 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 thyristors 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 in hoist drives), the motor will regenerate the energy back to the line in the most robust manner. This region of operation with oversynchronous regenerative braking is often used.

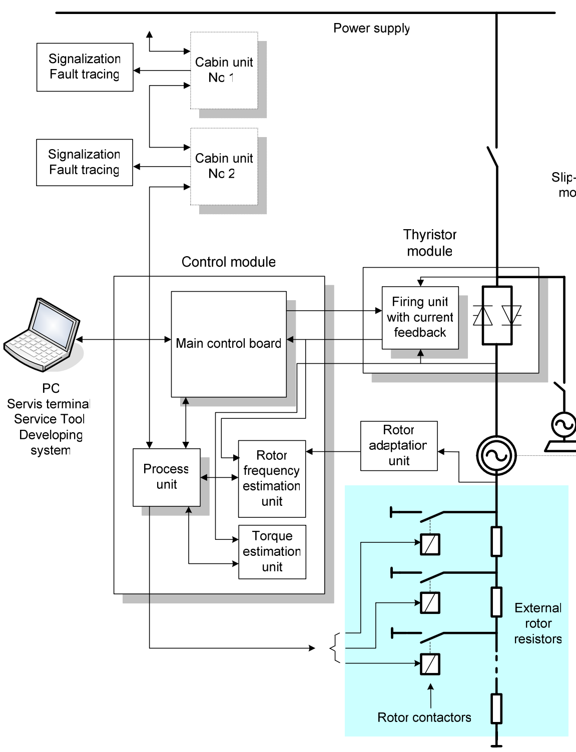


Fig.1 Structure of the industrial crane controller

This is because in the reverse current braking, as another solution, lowering close to synchronous speed would result in slip close to two, and consequently overheating additional external rotor resistors. It can be seen from the Fig.1. that the core of the systems is main control board (control module) realized on the MC68332 microcontroller, running the crane application program Control module generates the firing pulses to the thyristor module by means of a conventional wire, which limits the distance between these units to a few meters.

Rotor voltage frequency estimation unit estimates speed (slip) based on the rotor voltage frequency measurement and sends this information via the process unit to the main control board, [3]. Torque estimation unit estimates the machine torque based on the stator voltage and current measurement, [4]. Estimated torque signal is also sent to the main control board. Estimator units are based on the ADMC300 DSP board and included in the control system modular structure as a separate module. The main control board performs the speed control task and communicates with all other units in the drive controller, [5]. All control system connections to Master/Follower communication, Overriding control and Process control (including cabin I/O communication) are made by optical fiber, Fig.1. a). The communication is realized with two communication microcontrollers SAB82532. Details can be found in [5].

Speed or torque (selected via parameter) control loop with inner current control loop is presented in Fig.2. Controllers are generally PID type, with parameters and structure dependent on the specific applications. Control algorithm is running on the control board while the controller parameters settings, program downloading, monitoring and data recording are performed on the PC, Fig.1. It is possible to use mechanical speed feedback sensors (tachogenerator and incremental encoder) as well as speed estimator based on the rotor voltage frequency measurement, [3].

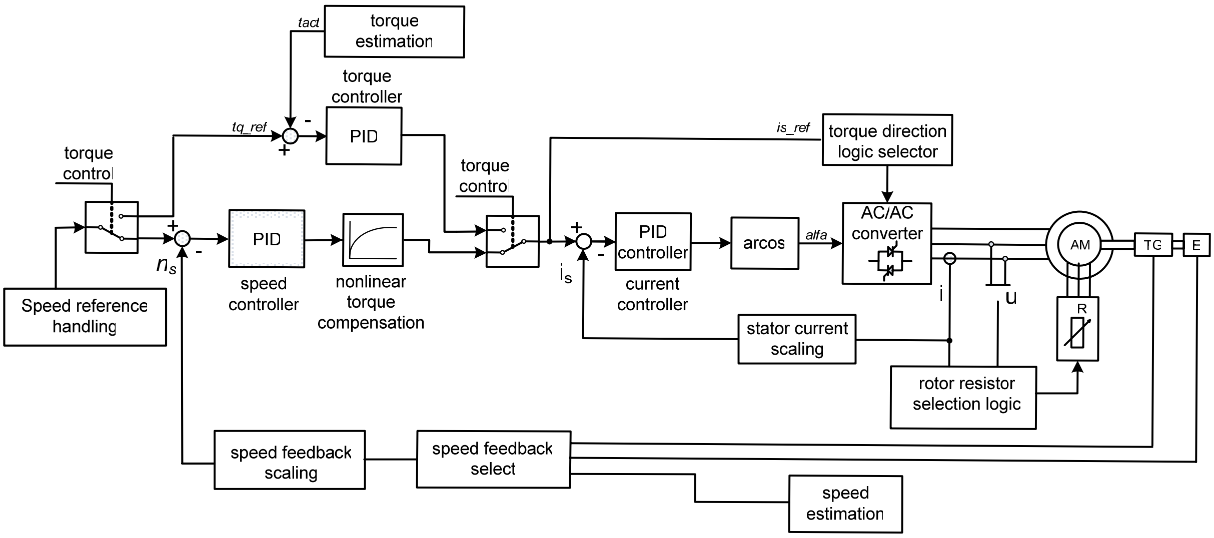


Fig.2. The speed control structure of the AC wound motor based industrial controller

3. ROTOR RESISTOR CONTACTOR SWITCHING LOGIC

Once upon a time, in the beginning of the AC machine control era, mainly one efficient speed control of AC machines for industrial application was used. That control was applied on the AC wound motor. It was focused mainly on the rotor motor side using speed-based rotor contactor switching for discontinuous additional external rotor resistor change. Stationary 'world' (stator) and rotational 'world' (rotor) were connected with simple interface; rotating rings and stationary brushes. Thanks to that, AC wound motor 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 wound motors for those tasks, because of its high robustness and very simple and effective speed/torque control from the rotor side. Nowadays, thanks to the refurbishment requirements associated to the wound motor, conventional rotor resistor switching logic is replaced by the advanced one. Herein, the new developed rotor resistor switching logic is presented.

As mentioned earlier, the new method is based in the on-line automatic optimization of the rotor resistors by means of rotor contactors. For any sampled motor speed, defined stator current limit, maximal torque available, resistor temperature and supply voltage, the main task is to find the optimal resistor to be switched in the rotor circuit in order to fulfill some optimal criterion. This criterion can be, e.g. maximal developed motor torque at this sample time, calculated for each additional external resistor. Among the all of calculated torques available for each additional rotor resistor, one resistor (the best in optimality sense) will be chosen and connected to the rotor by means of contactor. All contactors are handling by digital outputs (DO) of the process I/O board, Fig.1.

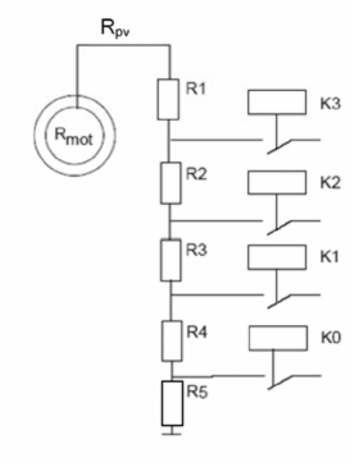


Fig.3. Schematics of the rotor resistor switching

The schematics of the 5 steps rotor resistors (R1-R5) with 4 contactors (K0-K3) driven by process I/O digital (DO1-DO4) respectively is presented on Fig.3. The resistor value ΣR_i has to be chosen according to specific industrial application. For different types of movements (e.g. hoisting, plug mode lowering, oversynchronous regenerative mode

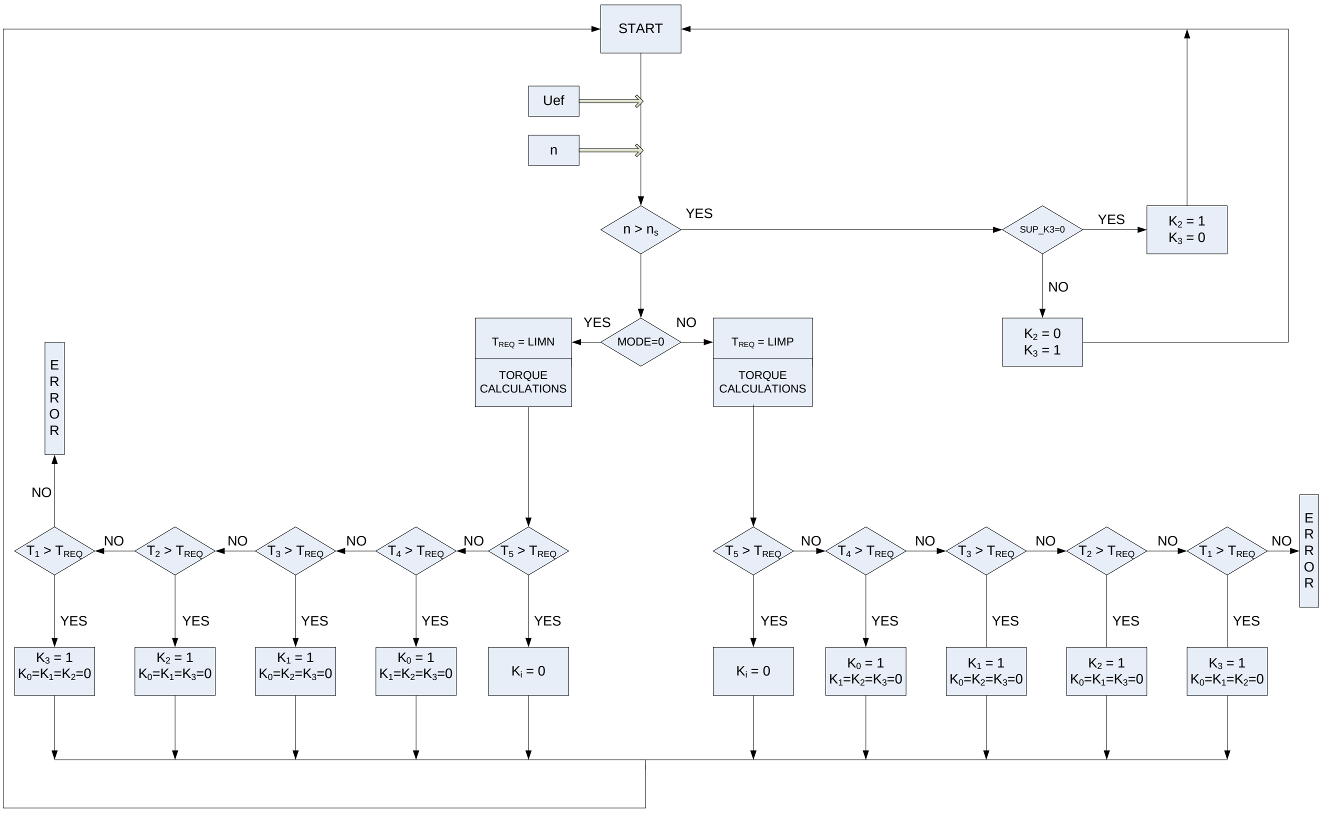


Fig.4. Flowchart diagram of the rotor resistor switching logic

lowering, traveling, etc), the values suggested in [2] give trouble-free performance in most situations. Resistor value ΣR_i is calculated as

$$\Sigma R_i = \frac{R_m + R_c + R_1 + R_2 + \cdot\cdot + R_i}{R_{100}} 100\% \,, \quad (1)$$

where R_i is ohmic value of the external rotor resistor R_i and R_{100} is unity resistance defined as

$$R_{100} = \frac{P_n}{3 \cdot I_r^2 (1 - s_n)} [\Omega] \,. \quad (2)$$

Unity resistance is defined as resistance that will hold the motor at zero speed with nominal load and nominal voltage. The values ΣR_i used in industrial applications are usually 8, 18, 38, 65, and 100% of the unity resistance R_{100}. The values $\Sigma R4$ and $\Sigma R5$ are only used for lowering, where the load requirement is lower than in the hoisting direction. The resistors R_m and R_c are defined as

$$R_m = R_{100} \cdot s_n [\Omega] \,, \; R_c \approx 0{,}02 \cdot R_{100} [\Omega] . \quad (3)$$

Here R_m is the rotor resistor value which gives nominal slip at nominal load and nominal voltage supply (in other words this is nominal slip part of the motors unity resistance) and R_c is ohmic value of the cable between motor and resistors.

Now all elements for R_i calculation, based on (1), are noun. Influence of the resistor change in dependence of the temperature, is considered throe the following equations

$$R_{iC} = R_i \cdot (1 - 0.9 \cdot (K_{\Delta R} / 100)) \quad (4)$$

$$R_{iW} = R_i \cdot (1 + 0.6 \cdot (K_{\Delta R} / 100)) \,, \quad (5)$$

where R_{iC} and R_{iW} are rotor resistors in cold and warm state and $K_{\Delta R}$ is percent change in resistor value caused by the temperature.

For the other initial calculation in Fig.4, it is needed to make a basic calculation. Stator voltage and rotor speed measurement are inherent in each wound induction motor controller based on the stator voltage and rotor resistor control, [1-5]. Before the maximal torques calculation logic starts (see Fig.4), mode of operation should be determined. This is because the rotor contactor logic is working in a different way for a different mode of operation. With the first decision block in flowchart diagram in Fig.4, it is assigned whether the drive is in subsynchronous or in oversynchronous (plugging or regenerative) region. For subsynchronous region of operation, operation mode is tested. Drive mode is defined on the base of direction of the motion requested, direction of the field (converter state), type of the motion (hoisting → potential loads, traveling → reactive loads) and actual motor speed. Motor must be able to produce requested torque (TREQ); LIMP requested torque for positive and LIMN for negative mode. Then the possible motor torques for each R_i resistor at each speed for cold and warm state are calculated according to equations

$$T_{iC} = MIN\left[\frac{2 \cdot U^2 \cdot T_M \cdot s_{iCM} \cdot s}{s^2 + s_{iCM}{}^2} ; \frac{I_{\lim}^2 \cdot U^2 \cdot R_{iC}}{s} \right] \quad (6)$$

$$T_{iW} = MIN\left[\frac{2 \cdot U^2 \cdot T_M \cdot s_{iWM} \cdot s}{s^2 + s_{iWM}{}^2} ; \frac{I_{\lim}^2 \cdot U^2 \cdot R_{iW}}{s} \right] . \quad (7)$$

Here T_{iC} and T_{iW} are possible torques in cold and warm state for i-th rotor resistors at slip s (as a multiple of nominal torque) and U and I_{lim} are supply voltage and current limit. At maximal (breakdown) torque T_M, slip in cold and warm state s_{iWM} and s_{iCM} is defined as

$$s_{iCM} = R_{iC} \cdot (T_M + \sqrt{T_M^2 - 1}) \quad (8)$$

$$s_{iCW} = R_{iW} \cdot (T_M + \sqrt{T_M^2 - 1}) \,. \quad (9)$$

What is the basic strategy? Check in order possible motor torques $T_5, T_4, .., T_1$ to find a T_i that is bigger than TREQ, Fig.4. As soon as the T_i is found, the right external resistor (i.e. right contactor switching according to Table 1.) is defined.

Table 1. Contactor switching logic

TREQ	K_0	K_1	K_2	K_3
TPOSS1>	0	0	0	**1**
TPOSS2>	0	0	**1**	0
TPOSS3>	0	**1**	0	0
TPOSS4>	**1**	0	0	0
TPOSS5>	0	0	0	0

It should be emphasized here that the rotor contactors should never be additionally controlled by any PLC or similar. It is important that the DOs of the controller directly handle the rotor contactors. It means that the rotor control is an integrated part of the real time motion control with 3 ms sampling time.

In order to help the user to calculate the resistor values and to study the result of the voltage fluctuations and current limits, the resistor checker application tool is designed. The application tool has two worksheets in Microsoft EXCEL environment. Based on the data of motor, voltage supply and resistor value ΣR_i selected, first sheet returns the nominal torque of the motor and the Ohm values of the resistor steps in the same sheet. The torque speed diagram is another tab of the worksheet, Fig.5. It is based on the data of the input sheet. The torque speed diagram is shown and by varying the input data, advanced simulations can be done and help to get good engineering solutions for the specified motion control, [2].

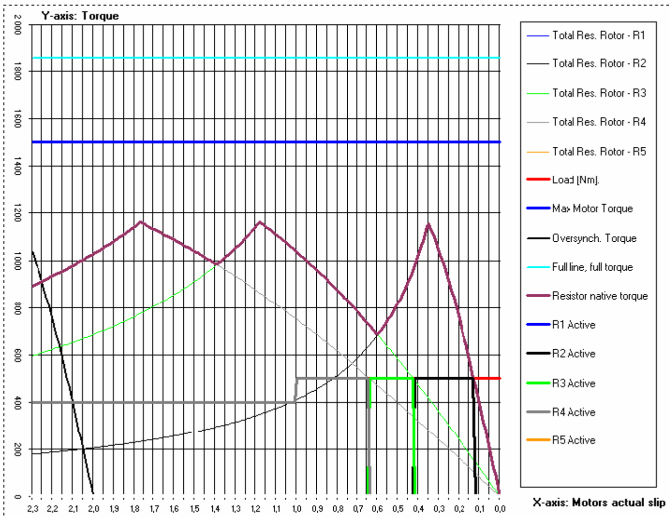
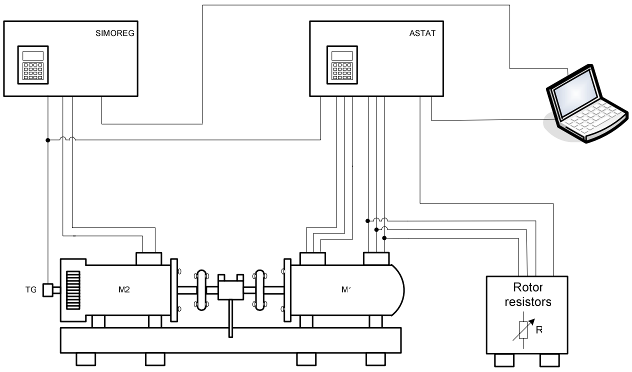


Fig.5. Rotor resistors checker worksheet

4. EXPERIMENTAL RESULTS

Comparison between conventional (manual, speed base rotor contactor switching logic) and proposed automatic rotor contactor switching logic has been performed on the laboratory test bench, Fig. 6. (Detailed description in [3-5]).



M1 – AC wound motor (380V, 18,5kW, 1450rpm)
M2 – DC separately excited motor (220V, 17kW, 1500rpm)
TG – tachogenerator

Fig.6. Laboratory test bench for experimental verification of automatic rotor contactor switching logic

Target AC wound motor driven with developed controller ASTAT is mechanically coupled with DC motor. The latter is driven by the SIMOREG controller in torque mode loading target AC motor. In Fig.7.and 8. the comparison between automatic and manual rotor contactor handler for no load a) and cca 80% rated torque b) is presented. Practically, there is no difference in responses. The steady state speed error in hoisting direction is a consequence of the inherent AC saturation characteristic (Fig.7b and 8b). The good performance of the automatic rotor contactor

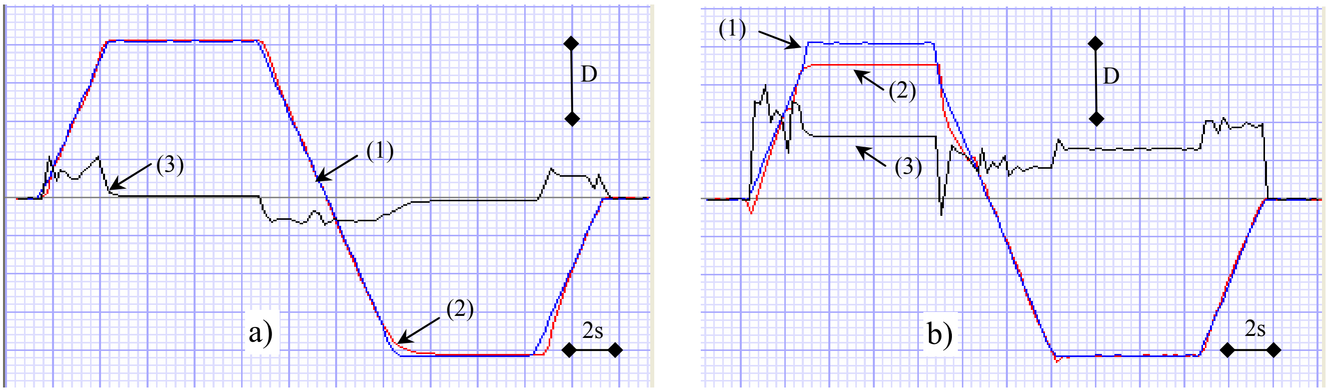


Fig. 7. Performance of the AUTOMATIC rotor contactor handler in one working cycle; hoisting mode with plugging subsynchronous braking with no load a) and cca 80% rated torque load b). Scale D=50% for ref.speed (1) and actual speed (2), 100% for motor torque (3).

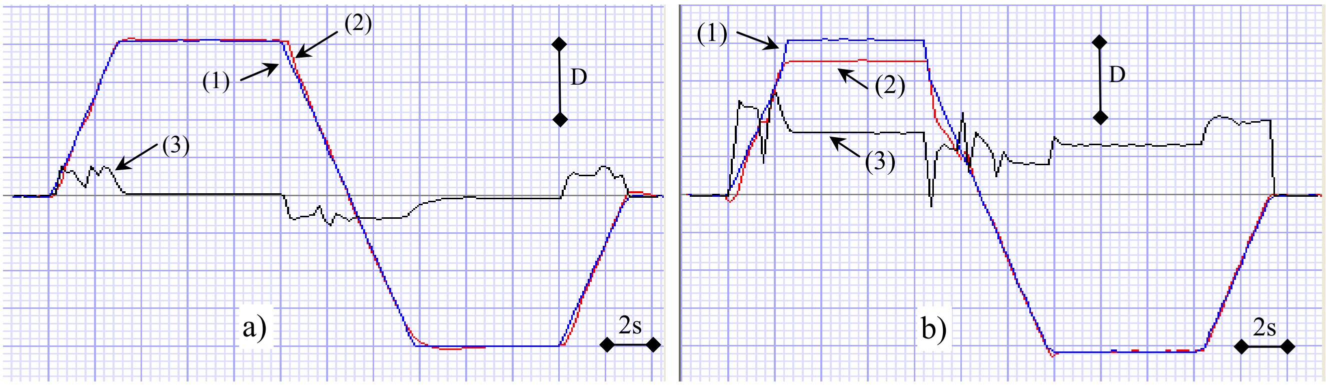


Fig..8. Performance of the MANUAL rotor contactor handler in one working cycle; hoisting mode with plugging subsynchronous braking with no load a) and cca 80% rated torque load b). Scale D=50% for ref.speed (1) and actual speed (2), 100% for motor torque (3).

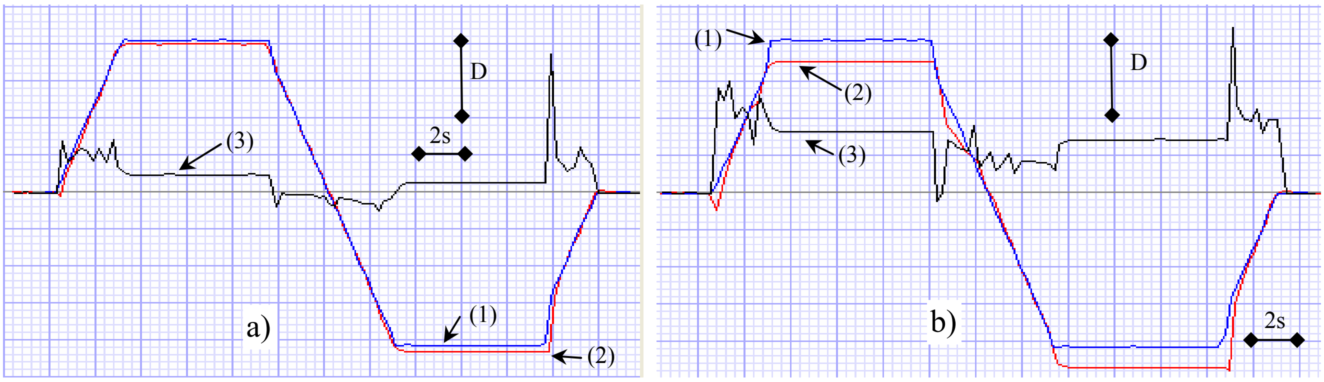


Fig. 9. Performance of the AUTOMATIC rotor contactor handler in one working cycle; hoisting with regenerative oversynchronous lowering braking, load 20% a) and 80% rated torque b). Scale D=50% for ref. speed (1) and actual speed (2), 100% for motor torque (3).

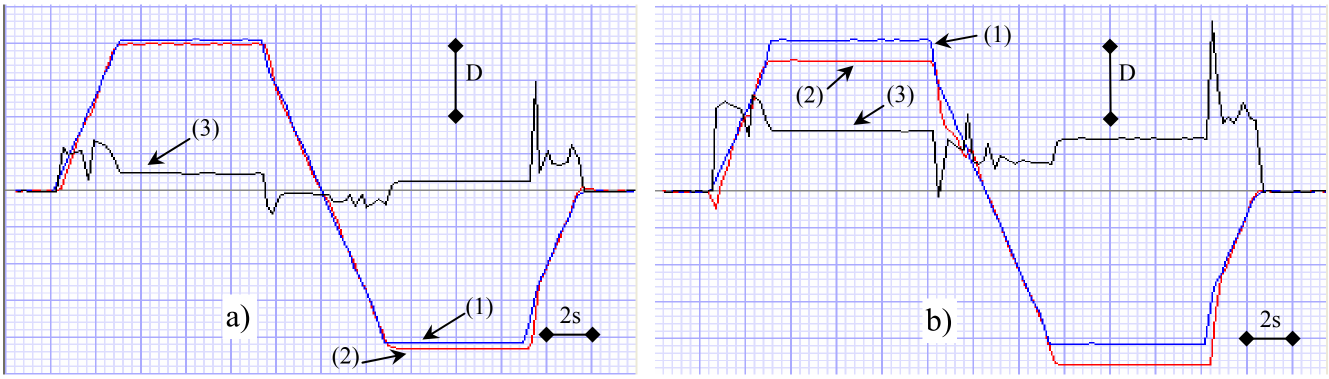


Fig.10. Performance of the MANUAL rotor contactor handler in one working cycle; hoisting with regenerative oversynchronous lowering braking, load 20% a) and 80%of rated torque b). Scale D=50% for ref. speed (1) and actual speed (2), 100% for motor torque (3).

handler is confirmed also in representative demand task – oversynchronous regenerative braking, (Fig.9.). It is obvious in comparison with manual rotor contactor (Fig.10.) that using automatic rotor contactor handler extra time and money for the commissioning will be avoided with the same control performances preserved.

5. CONCLUSION

This automatic procedure developed for the optimal rotor resistor switching is a part of the complex crane application program realized on the MC68332 microcontroller. However, electromagnetic motor torque needed for calculation, is running on the DSP ADMC300 and owing to modular controller design, the actual torque information is transferred to the main board thru fast RS422 link. Here is experimentally approved that algorithm for ON-LINE rotor resistor calculation has excellent features in all requested modes of operation and can replace successfully standard speed-based rotor contactor handler where contactor switching points has to be calculated in advance, each time for the new industrial application. From industrial point of view, this means no extra cost for additional commissioning caused by speed-based switching points determination.

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