REDUCTION OF THE STARTING LOSSES FOR THE WOUND ROTOR INDUCTION MOTOR

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REZUMAT. În acţionările grele (sute de kW), încă sunt utilizate motoarele asincrone cu rotor bobinat. În ciuda simplităţii reglării vitezei pe caracteristici reostatice, pierderile importante aferente metodei, mai ales la viteze mici, fac ca facilitate să fie utilizată doar pentru pornire. Chiar şi aşa, pierderile în rezistoarele suplimentare sunt importante. Articolul propune o metodă de pornire care nu mai apelează la rezistoare adiţionale şi deci, elimină pierderile corespunzătoare. Simulările confirmă viabilitatea metodei.

Cuvinte cheie: motor asincron, rotor bobinat, dublă alimentare, pornire.

ABSTRACT. In heavy duty drives (hundreds of kW), wound rotor induction motors are still used. Despite their simple capability to easily operate at variable speed, the large amount of losses which occur at low speeds determine the users to use the facility given by the wound rotor only for starting. Even so, the losses specific to the additional rotor resistors are quite important. The paper proposes a technique for starting which avoids the use of additional rotor resistors and consequently it eliminates the corresponding losses. The simulations confirm the viability of the technique.

Keywords: induction motor, wound rotor, doubly fed, starting.

1. INTRODUCTION

For high power (x 100 kW – MW) and heavy duty drives like pumps, fans, cement and minerals industries, hydro and wind generators, shaft generators for ships, wound rotor induction motors are generally used. In this range of power, generally, the stator windings are high voltage ones (6 kV). For such rated voltage the classical solution for variable speed drives which involves a controlled V/f source is difficult to be applied. Only few manufacturers are able to offer such solutions which cancel the necessity of a wound rotor machine, but the price is quite prohibitive.

For existing drives, the control on the rotor side is technically more accessible, knowing that the rated rotor voltage can be ten times smaller than the stator one. Thus, power electronic equipment is easily to be reached.

The paper proposes a solution for starting (and speed adjustment) high power heavy duty wound rotor asynchronous motors drives which would have a maximized efficiency thanks to the elimination of the losses specific to the additional resistors. The method, known as double feeding of the induction machine is presently used, as example, for speed adjustment of the asynchronous generators within the wind generators. The literature does not report the use of this method for starting the drives, knowing that the applications that use such type of motors need high starting torque. The literature [4] signals technical difficulties in using this method for speed ranges around zero (i.e. starting). The paper proposes a solution for extending the speed range down to zero.

The proposed solution dramatically improves the energetic efficiency of the variable speed drives with wound rotor induction machines, mainly during the starting process, grace to elimination of the power dissipation in the additional rotor resistances. It maintains in the same time the drive performances in terms of torque capability.

2. TECHNOLOGIES IN USE

In the present, for starting (and speed adjustment) of the heavy duty electric drives with wound rotor asynchronous motors, beside the classical solution which involves a variable three-phased additional resistor on the rotor side, two other solutions are used, both of them using additional resistors on the rotor side. Consequently, especially during the starting phase, but also during the speed adjustments mostly in the low speed range, important losses occur.

As example, Fig. 1 plots the stator active power and the dissipated rotor power during the starting of a 2.2kW drive with additional resistors, loaded with the rated torque.

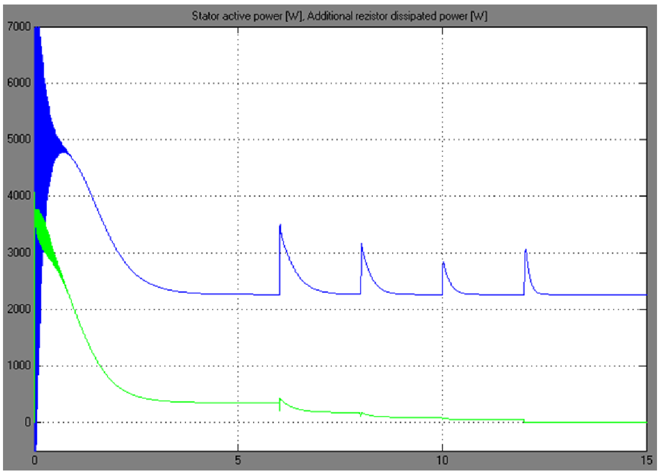

Fig. 1. Stator active power and rotor dissipated power during the start with additional resistors.

The amount of energy in the two windings during the starting process is shown in Fig. 2.

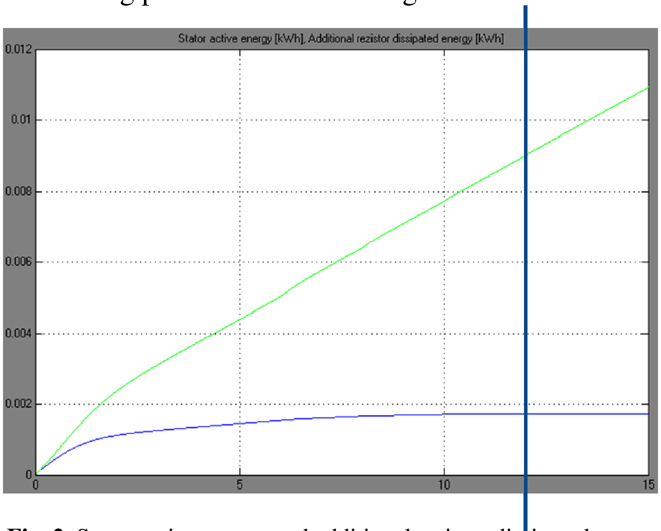

Fig. 2. Stator active energy and additional resistor dissipated energy during the start with additional resistors.

It is important to note that dissipated energy in the additional rotor resistor rises to 20 % of active power on the stator side.

The first of the two new technologies (Fig. 3) uses an uncontrolled rectifier supplied by the rotor winding. The load of this rectifier is an electronic variable resistor, by the way of a chopper.

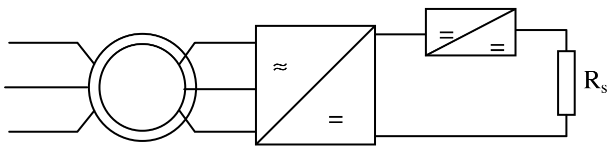

Fig. 3. Technology with uncontrolled rectifier and electronic variable resistor.

The chopper can be avoided if, instead of an uncontrolled rectifier is used a controlled one on the ground of the second technology described below. The equivalent resistance in the rotor side can be thus adjusted by the fire angle of the rectifier. The practical technical difficulties lie in the control part of the rectifier, knowing that the frequency on the rotor side is permanently variable. Thus, the classical "phase control" of the fire angle cannot be used anymore.

The second technology (Fig. 4) involves a graduator on the rotor side. The fire angle of the semiconductors adjusts the equivalent additional resistance in the rotor circuit.

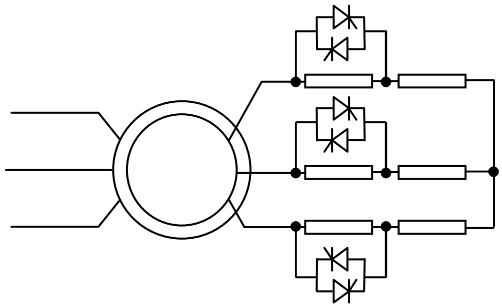

Fig. 4. Technology with graduator.

Two elements are common to the technologies described above:

- the both involves the direct connection of the stator at the power grid; this aspect is mandatory due to the high rated voltage of the stator (6 kV). As was stated above, for this voltage, it is not impossible, but is difficult to apply the V/f control on the stator side;
- the both use additional resistors. Besides the disadvantages given by the necessity of the additional resistors themselves (size, occupied space), during the operation, inevitable additional losses occur. The amount of the losses is higher if the drive must perform speed adjustment, especially in the low speed range, as losses are proportional to the slip. The amount of losses is unacceptable for current exploitation purpose.

3. PROPOSED TECHNOLOGY

In the range of high and very high power, speed adjustment of the wound rotor asynchronous machines can be achieved by applying the double fed principle.

The typical applications of doubly fed induction machines are high power drives (pumps, fans, cement and minerals industries), hydro and wind generators, shaft generators for ships etc. where operating speed range is about ±30% of the synchronous one. Consequently, due to the fact that only the slip energy is circulated by the two converters, only small power is spread by the static converters chain. As example, for a speed range of D=3:1 (0.5÷1.5 n_N), the rated power of the rotor side converter can be just about 0.33 of the machine rated power. This is the main reason why this method is used only for speed adjustment in limited range. If the principle must be used for starting too, the rated power of the converters chain will rise to the rated power of the induction machine.

The classical technology of this principle is the sub synchronous cascade. It allows the regulation of the motor speed, as the name is saying, only below the synchronous speed and it consists in retrieving of the slip energy from the rotor and reinsertion of this energy either in the grid or, as mechanical energy, at the motor shaft.

The real doubly fed principle consists in supplying the rotor winding by a bidirectional converter, the stator being directly connected to the grid (Fig. 5). Even the principle diagram from Fig. 5 is similar to the static sub synchronous cascade, the control principle for the double fed induction machine is different.

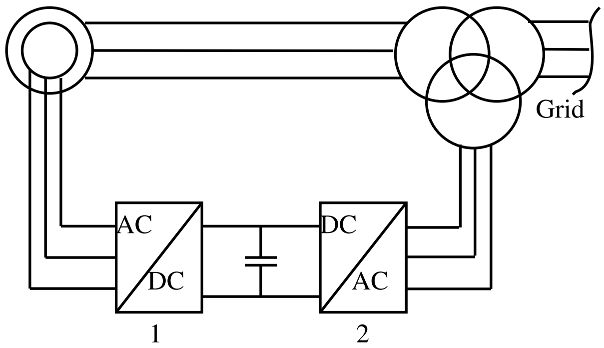

Fig. 5. Speed control by double feeding the asynchronous motor.

Thus, in the case of the sub synchronous cascade, the static converter 1 connected to the rotor windings is an uncontrolled rectifier, the energy corresponding to the induction motor slip being reinserted into the grid by the inverter (converter 2).

For the double fed machine, the both converters are bidirectional ones. In fact the two are fully controlled bidirectional bridges, able to circulate the energy in both directions.

The most "in fashion" application of this technology is the speed control of the wind generators for achieving the MPP operation, thus the machine runs in generator mode around the rated speed. It is the most suited application, as it does not need to be started, because the wind is used to accelerate the machine up to the operating speed range [1, 2].

As can be seen, the proposed solution is able to perform speed control on the both sides of the synchronous speed. This is another important facility of the solution, face to the classical sub synchronous cascade. Furthermore, the price of the converter can be more attractive than in the case of V/f converter on the stator side, taking into account the quite different values of the rated voltages on the two sides of the machine.

Another important advantage of this control technology is the short time maximum torque. For doubly fed asynchronous machine, this parameter is much higher than all other electric machines, including induction or permanent magnet machines. This is due to the fact that the increasing of the active current does not directly increase the air-gap flux and consequently the iron saturation. The active current is temporally limited only by the thermal stress of the windings and by the current capability of the rotor side converter.

Continuing with the advantages of the control technology, it must be mentioned the very important facility to control the reactive power changed by the stator with the grid. The term "changed" was used because, with a proper control of the rotor side converter, it is possible not only to cancel the reactive power got by the stator from the grid (unity power factor), but even to inject reactive power into the grid. This is a quite important advantage, taking into account the size and number of such drives in the mining industry, for example.

For motor operation, several reasons are mentioned in the literature which limits the use of this technology only for speed adjustment, not for starting too:

- high rotor to stator winding turn ratio. This generates at low speeds (standstill) very high voltages in the rotor windings, much higher than the rated one;
- if the technology is used for starting and speed adjustment in the low speed range, the rated power of the static converter chain must be designed for the rated power of the motor;
- high instability of the control in the very low speed domain (around zero).

This last aspect is highlighted in the results of the simulation of the 2.2 kW doubly fed induction machine drive. The control was performed by considering stator flux oriented control on the rotor side of the doubly fed induction machine. The two components of the rotor voltage are obtained based on the rotor voltage equation written in the stator-flux-oriented frame:

$$\underline{u}_{r\Psi s} = \left(R_r + L_r^{'} p\right)\underline{i}_{r\Psi s} + \frac{L_m^2}{L_s} p\left|\underline{i}_{ms}\right| + j\omega_{sl}\left[\frac{L_m^2}{L_s}\left|\underline{i}_{ms}\right| + L_r^{'}\underline{i}_{r\Psi s}\right] \tag{1}$$

with ω_{sl} the angular slip frequency.

The projections of (1) on the two orthogonal axes are:

$$T_r^{'}\frac{di_{rx}}{dt}+i_{rx}=\frac{u_{rx}}{R_r}+\omega_{sl}T_r^{'}i_{ry}-\left(T_r-T_r^{'}\right)\frac{d\left|\underline{i}_{ms}\right|}{dt}, \quad (2)$$

$$T_r^{'}\frac{di_{ry}}{dt}+i_{ry}=\frac{u_{ry}}{R_r}-\omega_{sl}T_r^{'}i_{rx}-\omega_{sl}\left(T_r-T_r^{'}\right)\left|\underline{i}_{ms}\right|. \quad (3)$$

By assuming constant stator flux operation, constant stator magnetizing current respectively and considering the imposed values of the currents, the decoupling components of the rotor voltage result:

$$u_{drx}=-\omega_{sl}L_r^{'}i_{ry}^{*}, \quad (4)$$

$$u_{dry}=\omega_{sl}L_r^{'}i_{rx}^{*}-\omega_{sl}\left(L_r-L_r^{'}\right)\left|\underline{i}_{ms}^{*}\right|. \quad (5)$$

In equations (1)-(5), the term $L_r^{'}$ is the rotor transient inductance.

The results of the simulation of the drive when the speed decreases to low values are plotted in Fig. 6.

The plot begins when the motor comes to be controlled in the rotor circuit, being supplied on the rotor side by a voltage source inverter. Until then the motor has the rotor in short circuit, being supplied in the stator by a constant frequency voltage (the grid) and loaded with a 10 Nm static torque. The stator continues to be connected to the grid after the control on the rotor side begins. The stator flux oriented vector control imposes constant active and reactive rotor currents. The reactive rotor current is greater than the rated one and the stator injects reactive power in the grid (plotted in the last window).

The active current is smaller than the one needed for balancing the static torque. Consequently, the speed constantly decreases. It can be seen that around 25 rad/sec the system became instable.

For the reasons pointed above, literature signals as starting method for this kind of drives the quite classical method with additional resistors in the rotor circuit. When speed arrives within the operating speed range, the resistors are disconnected and the frequency converter is connected to the rotor. Another possibility is to reverse the operation of the machine: short circuit the stator and supply the rotor by the static converters up to the necessary speed then switching the control types.

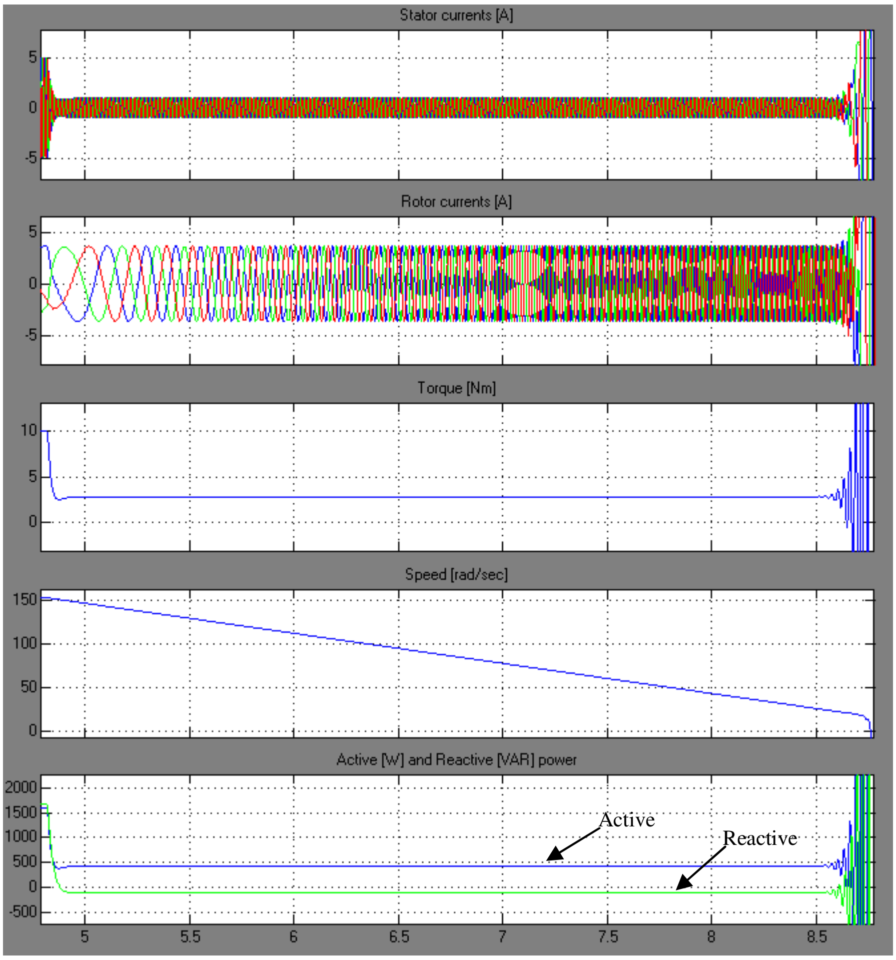

Fig. 6. Behavior of the doubly fed induction machine in the low speed range.

In the case of wind generators the technology of rotor control is very well suited, as they are driven by the wind turbine. Consequently, they do not need to be started, because the wind is used to accelerate the machine up to the operating speed range, when the rotor control comes to manage the operation. For this type of application, the vector control is not the single possibility. Literature signals as possible alternative the Direct Torque Control on the rotor side [5]. The experience of the authors [3] shows that this type of control requires very high performances control hardware due to the fact that the sampling period of the control system is exactly the minimum duration of the pulse width modulation. Consequently, in order to be able to achieve high frequency modulation and low ripple currents, powerful (fast) control systems are necessary.

The technique we propose is simply to supply the rotor side of the induction motor by a preset currents inverter.

The simulation diagram (Fig. 7) uses the model of a preset currents voltage source inverter (P3Htg) which injects the necessary currents in the rotor windings. The two orthogonal components of the rotor currents result as outputs of two continuous PI controllers: the direct component is the output of the reactive power controller and the quadrature component is the output of the speed controller.

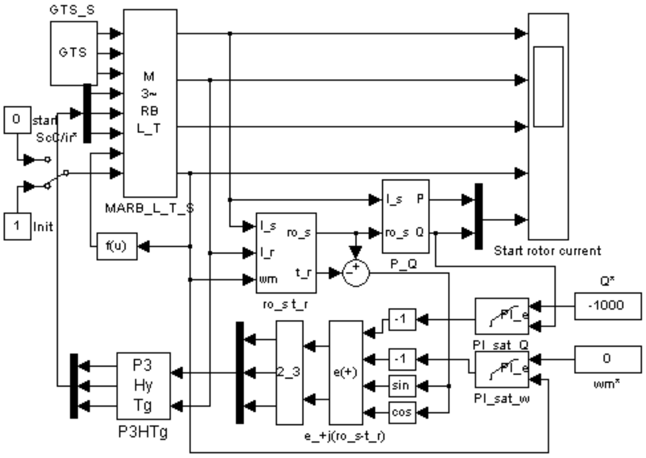

Fig. 7. Doubly fed induction machine supplied by preset currents voltage source inverter.

Some results of the simulation of the system are plotted in Fig. 8. The torque applied to the motor shaft is proportional to the mechanical speed. It attains the rated value at the rated speed.

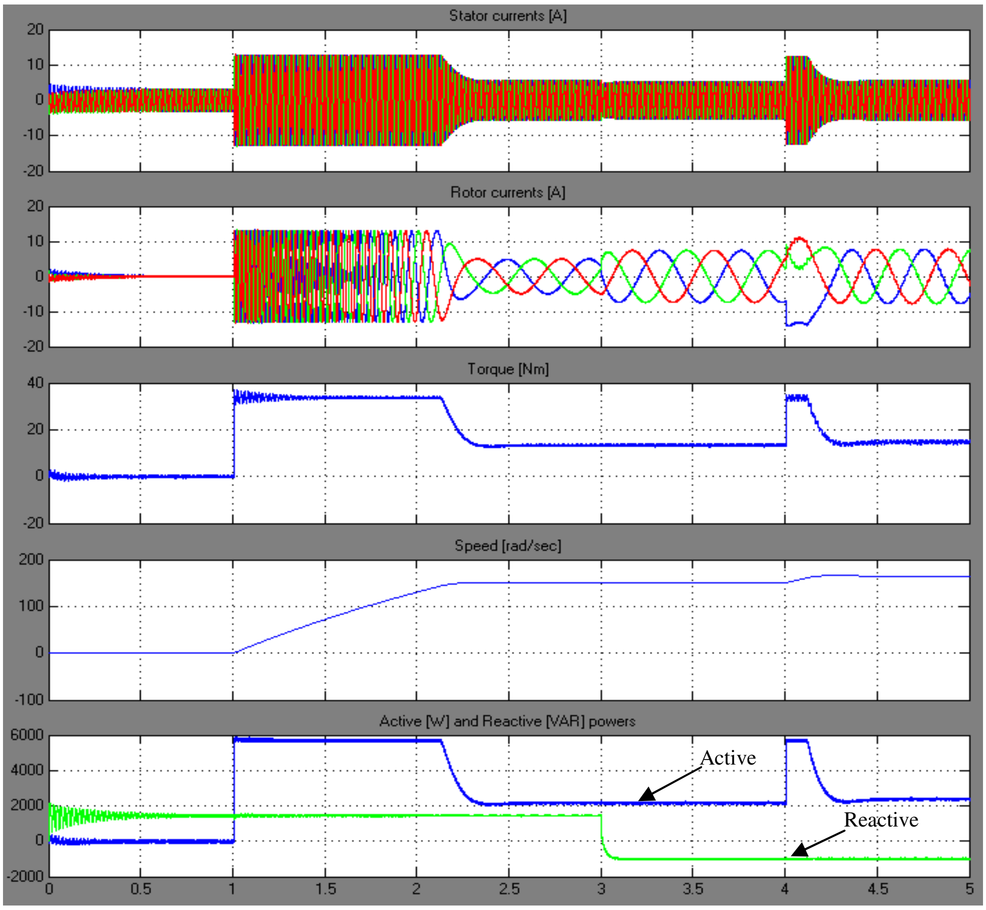

Fig. 8. Behavior of the doubly fed induction machine supplied by preset currents voltage source inverter.

The hyper-synchronous operation is imposed at 4 seconds after the beginning of the simulation, when the preset speed becomes 165 rad/sec, the synchronous one being 157 rad/sec.

It is notable the very good behavior of the drive during all the phases of the simulation.

The two reasons for using the double fed technology only for speed adjustment and not for starting too explained above are not always valid.

On one hand, the motors used in several existing applications have low (less than 1) rotor to stator winding turn ratio, i.e. the rated rotor voltage is much less than the stator voltage, up to 1 tenth. Consequently, the risk of over voltages on the rotor side there is not present anymore, with the price of quite important currents.

On the other hand, even for starting, the rated power of the motor is to be delivered by the rotor converter, does not imply severe technical problems because the technology is mature enough to be able to offer high power converters having the rated voltage in the range of 1 kV.

Besides the very truthfully behavior, an important disadvantage must be noted. It is the preset current modulation technology of the inverter. It is known that this type of modulation is specially suited for low power applications.

Another mentioned disadvantage of this modulation strategy is the variable switching frequency which has bad influence on the switching losses estimation in the designing phase.

The mentioned disadvantages could be minimized if the preset currents modulation would be used only for the very first moments of the starting process of the wound rotor induction machine. After the speed would arrive in the zone where it could be controlled by the way of a voltage source inverter (unstable at very low speed), the controlled would be switched. This subject, as well as the practical experimentation of the solution, are ideas for continuation of the research.

4. CONCLUSIONS

- ✓ The paper discusses the existing technologies involved in the variable speed drives based on wound rotor induction machines and proposes a technique for starting which avoids the use of additional rotor resistors and consequently it eliminates the corresponding losses.
- ✓ It implies the double fed of the induction machine and vector control of the currents injected in the rotor windings. It is shown by simulations that the voltage source inverters determine instability in the low range of the speed. The paper proposes the using of preset currents voltage source inverters which, even have known and notable disadvantages, are capable to truthfully control the drive, especially its start.
- ✓ Further researches will focus on minimization of the disadvantages of the preset currents modulation strategy.

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SERGIU IVANOV was born in Hunedoara, Romania and went to the University of Craiova, where he studied electrical engineering. He obtained his degree in 1986. He worked for the Institute for Research in Motors, Transformers and Electrical Equipment Craiova before moving in 1991 to the University of Craiova. He obtained his PhD in 1998 with a topic in the field of the control of the electric drives systems. He is involved in modelling of the electromechanical systems.