New Features Regarding Pumps Command by Electrical Drives

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Abstract: - As compared to hydraulic, pneumatic, or thermal motor devices, electrical drives have certain advantages owed to the ease of generating, transporting and distributing the electrical energy. This fact made them become the first choice in most of the cases emerging in actual activity. The present paper simulates the behavior of electrical drives powered by continuous current motors. The efficiency optimizing of the drive systems in industrial and modern appliances can be done through using vector control with DSP and intelligent power module for asynchronous motors. The authors contribution to this paper refer to the proposal and development of a control system of a rotation AC motor with field oriented control based on the signal processor TMS320F2812 DSP.

Keywords: - Drive system, Vector control, DSP, Intelligent power module, Nonlinear command.

1 Introduction

Classification of electrical drives systems will be done according to the degree of complexity in interpreting information, which actually denotes the evolution of the concept of electrical drive in time. From this perspective electrical drives systems fall into three categories:

- systems with sequential elements (non-automatic),
- systems with automatic regulation of certain parameters
- systems with process computers.

Quality in revolutions regulation comes from several quality parameters, among which:

1. Regulation range – defined by the ratio between maximum and minimum number of revolutions achieved by the suggested drive. It usually ranges between (1....1000), however there are more sophisticated drives with a wider range (1....20000).

2. The direction of regulation – how the number of revolutions varies as compared to the nominal ones. If the regulation system allows revolutions variation only under the nominal ones, or exclusively above the nominal ones, there is an inferior or superior mono-zone regulation. If the system allows regulation in both directions, we speak about dual-zone regulation.

3. Fine regulation – is the ratio of two adjacent revolutions, within the regulating range achieved; in this respect, some methods allow continuous regulation of the number of revolutions (the ratio above tends to 1), others allow regulation in steps.

4. Regulation output – motor system output – speed regulation device. Certain methods use regulation resistances, and the regulation output is low, hence they can be considered only for reduced power.

5. Regulation nature – the modality in which regulation is performed. Certain technological processes require that revolutions regulation should be performed at constant torque (lifting machines), others at constant power (tool drives).

The static converters in industrial processes are used mainly in the following applications: industrial drives adjustable (hydraulic, pneumatic, electrical and combined), the command and control of processes in the field of chemical, metallurgical and nuclear [1], [2]. Static converters are made up of semiconductor devices (static switches) and ancillary components (coils, transformers, capacitors, etc.), used to modify one or more characteristics of the electric power supply system [3], [6]. It is estimated that currently over 65% of the electricity produced is consumed in the drives in different areas by fans, pumps, compressors, machine tools, lifting equipment, robots (automated manufacturing lines) [4], [7], [9].

2 The Mathematical Model for the Continuous Current Motor

In order to determine the mathematical model for the continuous current motor, the starting point is the voltage equation for the induced circuit:

$$\begin{cases} u = R \cdot i + L \cdot \dfrac{di}{dt} + e \\ e = k_e \cdot \varphi \cdot \omega \\ m = k_m \cdot \varphi \cdot i \\ m - m_r = J \cdot \dfrac{d\omega}{dt} \end{cases} \tag{1}$$

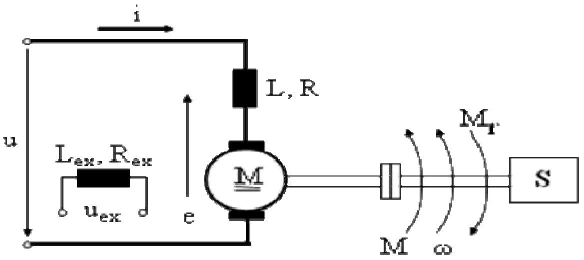


Fig. 1: Continuous current system drive.

Equation system (1) is non-linear, owing to the multiplication results of type $(\varphi\cdot_i)$ and $(\varphi\cdot_\omega)$ respectively, as well as to the non-linearities generated by the magnetization curve of the motor. Since the use of non-linear mathematical models implies complicated mathematical formalities, the system will be linearizaed around a functioning point, neglecting infinitely small variations. In order to do this, the excitation flux is considered constant, so that multiplication results $k_e\cdot\omega = K_e$ and $k_m\cdot\omega = K_m$ should be constant and computed by the following relations [5], [8]:

$$K_e = \frac{U_n - R_n \cdot I_n}{2\cdot\pi\cdot n_n}\left[V/rot/min\right]$$

$$K_m = \frac{K_e}{1,03}\left[Kg\cdot m/A\right]$$

With these notations and applying Laplace transformationin initial null conditions, the mcc transfer function is obtained under the form:

1. Transfer function as compared to the entry:

$$H_{MCC}(s) = \frac{\Omega(s)}{U(s)} = \frac{1/K_e}{T\cdot T_m\cdot s^2 + T_m\cdot s + 1} \tag{2}$$

2. Transfer function as compared to the perturbation:

$$H'_{MCC}(s) = \frac{\Omega(s)}{M_r(s)} = -\frac{\frac{T_m}{J}\cdot\left(1+Ts\right)}{T\cdot T_m\cdot s^2 + T_m\cdot s + 1} \tag{3}$$

2.1 Automatic Revolutions Regulation Systems in Continuous Current

2.1.1 Irreversible automatic revolutions regulation system for the continuous current motor, with simultaneous limitation of current

This is a regulation system with multiple loops or cascading, and it is preferred in electrical drives, as compared to independent regulators systems (of revolutions and current, each with its own reference parameter) or as compared to the ones with only 1 regulator for the main variable (number of revolutions) and with limits for the secondary variable(thecurrent).

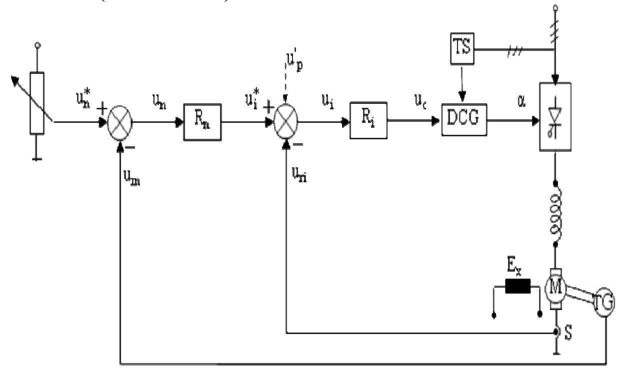


Fig. 2: Irreversible cascade regulation scheme for the continuous current motor.

2.1.2 Reversible automatic revolutions regulation system for the continuous current motor with simultaneous limitation of current

The system has a single revolutions regulator R_n and two current regulators R_{i1}, R_{i2}, one for each possible direction of rotor current. The two current regulators cannot function simultaneously because of the two diodes.

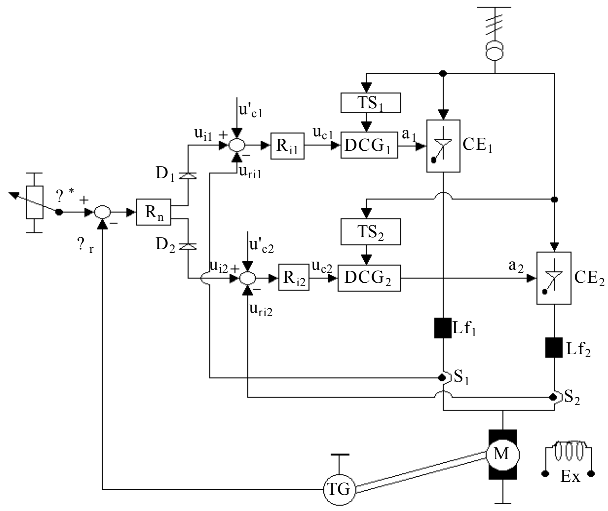


Fig. 3: Structural scheme of regulation.

2.1.3 Automatic revolutions regulation system for the continuous current motor, by weakening the excitation flux

When increasing the revolutions regulation range of the electrical motor is required, automatic systems are used as they allow modifications bothin the input voltage and the excitation current i_e. Such systems are achieved via combining the systems allowing voltage regulation with systems allowing excitation current regulation.

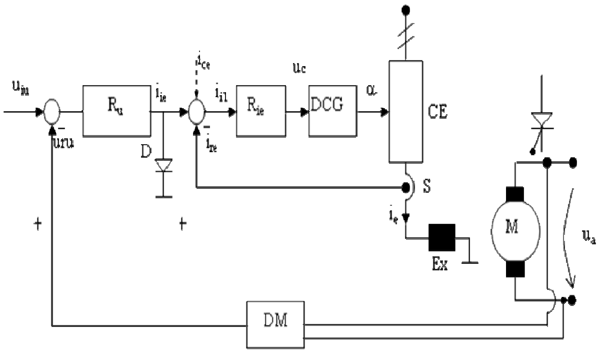


Fig. 4: Irreversible cascade regulation scheme for the continuous current motor.

3 Automatic Regulation Systems for Drives in Alternative Current

Asynchronous machines, usually three-phasic, have wide applications in electrical drives, as a result of the advantages they hold as compared to other drives, namely: simple and robust construction, safety in operation, low cost, direct plugging to the alternatve current sgrids [10], [12].

3.1 Three-phasic Asynchronous Motors Revolutions Regulation

According to the analytical expression of the three-phasic asynchronous motor number of revolutions [11]:

$$n = n_1 \cdot (1-s) = \frac{f_1}{p} \cdot (1-s) \quad [\text{rot/s}] \tag{4}$$

it becomes obvious that the number of revolutions can be altered by: modifying input frequency f_1, modifying the number of pole pairs p, or modifying slide s.

3.1.1 Modifying the number of pole pairs *p*

Modifying the number of pole pairs p leads to a discrete alteration in the rotation speed of the motor. Changing the number of pole pairs is done either by modifying connections in stator spires, or by fitting the motor with spires having different numbers of poles, or by combining these two methods. Modifying the number of pole pairs is done only in asynchronous motors with a cage rotor (in shortcircuit), as the cage is enabled to automatically adapt its number of pole pairs to the number of pole pairs of the stator. Modifying the number of pole pairs by 1/2 ratio can be performed relatively easily by modifying the connections of stator spires (the best known being the Dahlander), thus obtaining the two-speed synchronism asynchronous motor. This motor is provided with statoric coiling consisting in two halves for each phase (for the first phase the halves are U_1U_2 and U_3U_4). The halves on each phase can be serially connected (Fig. 5.b,c) or in parallel (Fig. 6b,c.).

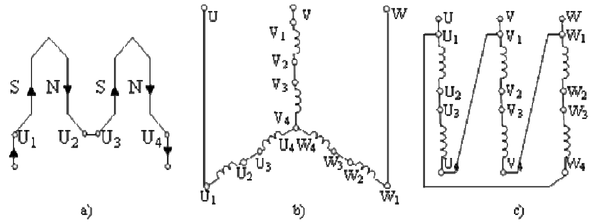


Fig. 5. Serial connection for stator coiling.

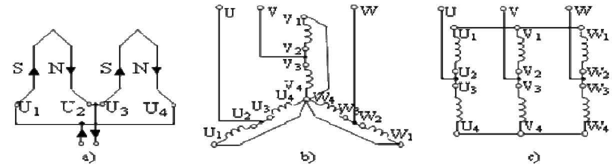


Fig. 6: Parallel connection for stator coiling.

3.1.2 Slide modification

When studying alterations opportunity for the number of revolutions via slide modification, the starting point is the approximate relation written for slide in the form [6]:

$$s \cong \text{const.} \frac{R_2^{'}}{U_1^2} \cdot M_r \tag{5}$$

This last relation is indicative of the fact that slide varies inversely commensurated with the square of input voltage, and commensurated with rotor resistance. As voltage U_1 can only be decreased as compared to the nominal value, and resistance can only be increased as compared to the value of phase resistance, the conclusion is that slide modification in the motor can be done only by increasing it,therefore only by decreasing revolutions number, obtaining mono-zone revolutions regulation. Moreover, considering Joule losses in the rotor circuit as commensurate with slide *(P_{J2}=sP)*, the consequence is that for a given load torque M_r, regulation output decreases with slide increase.

3.1.3 Modifying the frequency of input voltage

Regulating revolutions number by modifying the frequency of input voltage is achieved powering the motor from a frequency converter, which can be an inverter or a cyclo-convertor. Frequency cannot vary independently from the voltage input. Indeed, neglecting the voltage on phase impedance of the motor stator, the following is true:

$$U_1 \cong E_1 = 4,44 f_1 w_1 k_{w1} \Phi_m = \text{const} \cdot f_1 \Phi_m \tag{6}$$

where U_1 is the effective phase voltage appliedto the motor. So as not to impact on motor performance (torque, current operation to empty, nominal current), the magnetic flux Φm must stay constant, inasmuch as possible. It is therefore deduced that the ratio $U_1/f_1=const.$, meaning the voltage must be commensurate with frequency. This relation is adopted when frequency f_1 decreases up to the nominal value. When the frequency exceeds the nominal value, voltage U_1 remains constant ($U_1= U_{1n}$), as a result of isolation and increase in iron losses, so that, with frequency increase over the nominal value there is a decrease in the magnetic flux Φ_m.

The solution most frequently used to overcome this inconvenience is the system of regulating target field, called also adjustment vector or control vector, in English using the names: FOC (F*ield* O*riented* C*ontrol*) UFO (U*niversal* F*ield* O*riented*) or Vector control. The principle of targeting field of AC machines is to separate the dignitaries that produces the electromagnetique torque from the ones which produce flows of magnetization. By this method of regulating the asynchronous machine is controlled like a DC machine in which the electromagnetic torque is given by the scalar product of flow excitation and the current from induced, quantities which are independent.

The system of equations describing the relationship between electrical quantities characteristic to the machine, the developed electromagnetic torque and the connection with the mechanical quantities represents the mathematical model of asynchronous motor. The models with concentrated parameters are divided into two basic categories: models in phase coordinates and models using orthogonal axes.

Starting from the notation: p – the number of pairs of poles, θ_m - mechanical angle, $\theta=p\cdot\theta_m$ - electrical angle, $\alpha=p\cdot\theta_m+2\pi/3$, $\beta=p\cdot\theta_m+4\pi/3$, $\omega=d\theta/dt$ - rate of electrical rotation of the rotor, Cem electromagnetic torque RS, LS, RR, LR - characteristic parameters of the three stator windings, rotor respectively. Since there are different windings, the resistors RS, RR and their reactance's flaws are different, while their mutual inductance is the same, then the original model of asynchronous machine with squirrel-cage will be:

$$[U]=[R]\bullet[I]+[L]\bullet\frac{d}{dt}[I]+\omega\bullet\frac{d}{dt}[L]\bullet[I]$$

$$C_{em}=\frac{p}{2}\bullet[I]t\bullet\frac{d}{dt}[L]\bullet[I] \qquad (6')$$

There is another category of methods of adjusting the speed, which made direct torque control, grouped under the abbreviated name of DTC (D*irect* T*orque* C*ontrol*) [10]. In this case, in addition to flow control, the stator typically is intended to maintain constant torque machine developed by finding a best vector for the inverter switching voltage that feeds the machine. Control scheme is somewhat simple, dynamic performances are similar to those of Target field adjustment. As a disadvantage in compared with the FOC may be mentioned the lack of direct control over the machine currents which can create problems at start and rapid change in command torque.

Implementation of the adjustment vector with AC motors requires a substantial computing effort, while sampling periods which maintain the control in real time can not exceed 200-300 μs [5]. A vector control system is obtained in real time using digital signal processor DSP. It is widely recognized that DSP processors offers one of the best combination of integration, flexibility, efficiency and performance. How systems shareholders are becoming more complex and, accordingly, increase the complexity of control, the design of such systems becomes a difficult task in absence of efficient controllers that can be, in turn, designed in an environment friendly development.

Thus, the combination of power devices with improved performance of conduction and switching, and control offered by the DSP creates the conditions for optimizing the efficiency of industrial shareholders and modern appliances. Therefore, the objective of the paper is creating a vector control system with DSP and intelligent way to power motors.

In Fig. 7 is presented the electric drive system. The input Filter includes hardware protection, EMI filter and optionally a block correction of power factor (PFC), which can be controlled through outputs from DSP TMS 320 F 2812, produced by the company Texas Instruments. The correction circuit of CFA supplier factor may contain a battery of capacitors required for smoothing the continuous voltage from the charger's exit and a brake circuit that eliminates the energy stored in the motor.

As noted, the scheme is based on measurement of two phase currents and motor speed. Measured phase currents, ia and ib, are used to calculate the "Flow model" motor equivalent (Fig. 8), which is also based on information provided by the encoder speed, calculation done by DSP processor. Using DSP and vector control for electric drive system with asynchronous motor has the following advantages: high capacity torque at low speeds, good dynamic behaviour, and high efficiency in a broad range of speed, short time overload capacity, possibility of operating in four quadrants.

The command of this drive system is operated using vector regulation known as "indirect vector control after flow runner”, described above. Compared to the classical scheme it adds an additional block “field weakening” necessary for flow control motor. To increase speed, we increase the frequency of inverter control, and thus the supply voltage of the motor up to a maximum value (nominal value), corresponding to nominal speed, while maintaining constant flow motor. In normal conditions flow is maintained constant but increasing speed over the nominal value is due to weakening (lower) flow. In this application we use a three phase motor with star connected stator coils and rotor cage. The parameters of this motor are: rated power 0.5 kW, rated voltage on phase 220 V, rated current of 1.2 A, synchronization speed of 1,500 rpm, the number of pole pairs is p=2, the slip is 0.066, the moment of inertia of the rotor is $0.95*10^{-3}$ kgm^2, winding resistance is $0.95*10^{-3}$ kgm^2, stator windings resistance is 34.8 \ and the nominal torque [14]:

$$M_{nom} = \frac{P_{nom}}{\omega_{nom}} = \frac{500}{\left(\frac{2\pi\times 1400}{60}\right)} = 3{,}41Nm \qquad (6'')$$

has triggered also the development of new power semiconductor devices (modules with power transistors, IGBT transistors, other high performance devices with isolated grid, hybrid systems, intelligent modules). The intelligent power modules for industrial motors incorporate the power floor with an integrated control board in a package that has the same area of silicon. They allow designers to achieve the highest levels of energy efficiency, compactness and low EMI interference. Due to its high level of integration, these modules greatly simplifies design, reduces time to market and total cost launch system where they are used. Compared to discrete approaches, these highly integrated modules provide not only a great economy of space, but also eliminate time-consuming tasks for testing numerous discrete components. For this application we used the intelligent power module PM15RSH120 produced by Mitsubishi, one of the best known in this field worldwide [12].

This module includes: the complete power circuit (6 IGBT transistors of an IGBT inverter and additional IGBT transistor for braking), forming

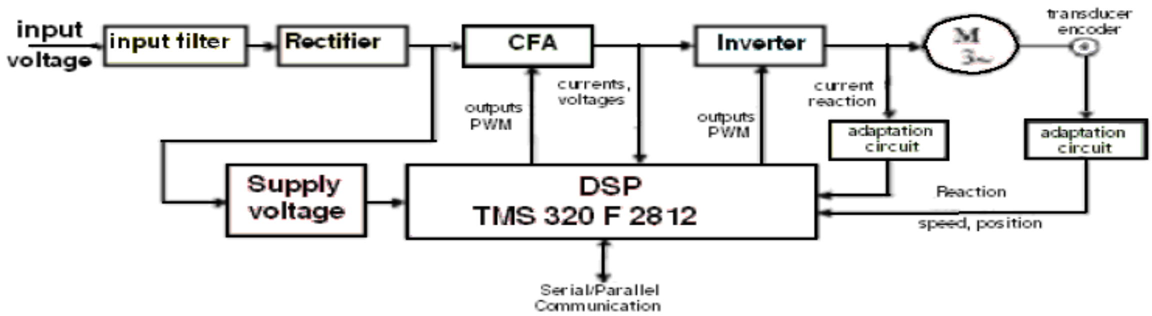


Fig. 7: The block diagram of an electric drive system with DSP and AC machine.

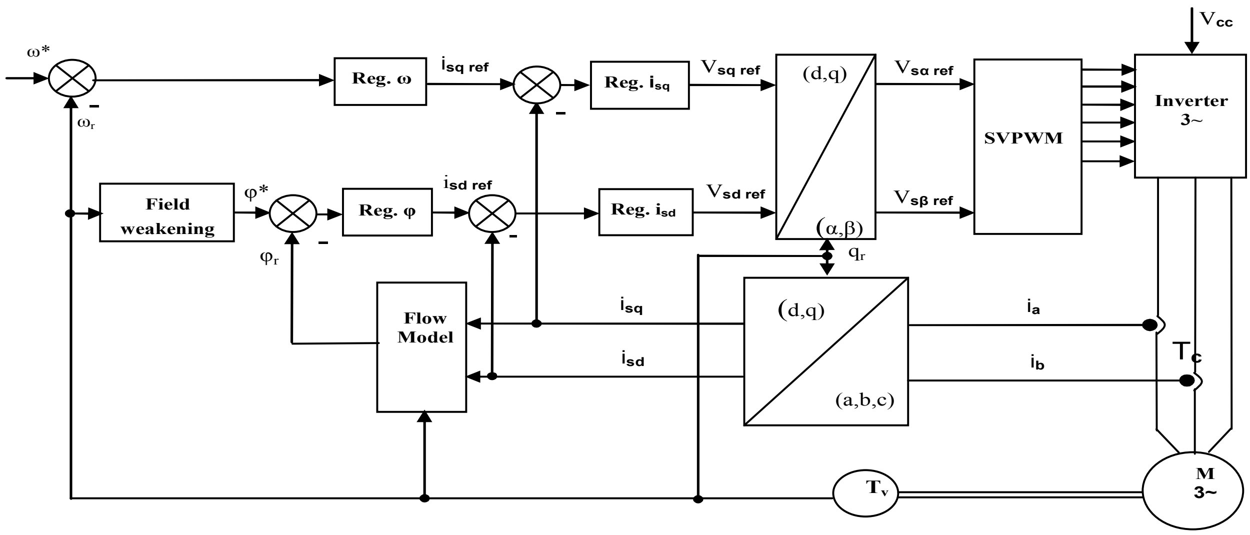


Fig. 8: The block diagram of the advanced vectorial control of an asynchronous motor.

The revolutionary development of electronic systems and power semiconductors in recent years

and control impulse circuits of each transistor, logic circuits protection (shortcircuit, overload, low voltage and at high temperature). He has the following parameters: rated current 15A, maximum continuous power voltage 1200V, maximum command frequency 20 kHz, the lock time delay (dead time) is 2.5 μs minimum. DSP sums the state of logic circuit of protection.

Connecting intelligent module to TMS 320 F 2812*DSP is illustrated in Figure 3 (asterisk * occurs because the structure of DSP's, and other circuits is also attached to be presented later). The input and seven outputs (which control transistors IGBT) of DSP are galvanically isolated from the module with optocouplers. The DSP input (pin 4 in Fig. 9) sums up the state of logic circuit protection. Enabling protection, when one of the situations described above occurs, determine the absorption of a current (10-15 mA) by the FO module inputs and forces to start the conduction of electroluminescent diodes of optocouplers.

The measuring current for protection and adjustment is made using LEM transducers family LTSR, because of the advantages they have: broadband spectrum, exact reproduction waveform at the output transducer, excellent accuracy and temperature stability, greater flexibility in applications being designed to be connected directly to a DSP [13].

The vector control structure requires the current measurement on two phases of the engine. They have been used to measure current two LEM transducers because of their advantages and have been listed before. From the LEM transducers range was chosen the type LTS 6-NP which can be configured to measure a nominal value of 2 A for the primary current, a value close to the rated current of the motor, ensuring a good accuracy of measurement. The operation of these current transducers and their transfer characteristic were presented in chapter two, along with a circuit adaptation for an analogue digital converter with a range of entry variation 0-3 V. Since DSP processors TMS 320 F 2812 are equipped with analogue digital 12 - bit converter, where entry can change in a range of 0-3 V, the circuit adjustment is the same as described above. The digital analogue converter will provide a value $x=n(V_{ref}/4096)=n(3/4096)$, where n is the number of quanta. It means that adjustment circuit to provide the output signal equal to: 0 V to a measure current $-I_{max}$, 1.5 V for a measure current null and 3 V for a measure current Imax. Current value through a phase of motor will be:

$$I=[I_{max}/(V_{ref}/2)](x-1.5)=[I_{max}/(3/2)](x-1.5) \qquad (6''')$$

To measure the engine speed we use a bi-directional incremental encoder with N=1000 pulses/rotation. The encoder provides the signals A, B, I (or Z) and possibly their complementary signals. Using signals A and B we determine the direction of rotation of the engine, and signal I switch to a full rotation. The speed calculation is made taking into account that the maximum number of pulses counted for one full rotation is 4xN, because for the detection of the direction of rotation, it is necessary to follow the sequence of values of the channels A and B: 00, 01, 10, 11, which may be used also for multiplying pulse. In the same time with the start of counting (metering) pulses NC from the transducer, the timer also is activated and so the time Δt corresponding to them to be known (pulses N_C). After one full rotation the signal Index/Zero is activated and will reset the two timers and pulse counting N_C. Thus, the speed, expressed in revolutions per minute, will be determined with the following relationship:

$$n=\frac{N_C}{4\times N}\times\frac{60}{\Delta t}=\frac{N_C}{4000}\times\frac{60}{\Delta t} \qquad (7)$$

The system includes: a power circuit to power induction motor, a method of measuring and adjusting the current, speed measuring circuit and system development (based on DSP). The components have a structure that differs more or less than the conventional (recognized). Thus:

- Circuit strength achieved with intelligent power module, which includes both the control and protection;
- Circuit current measuring and adjusting the phase current measurement allows the engine to current transducers with Hall effect due to their advantages: excellent accuracy, high linearity, low temperature derived for response time, broadband frequency not introduce losses in the circuit, measuring current exceeded bear without damage;
- Measurement of speed is achieved with an incremental encoder with 1000 pulses / rotation, adapted level signals we developed with a collector in the empty gates at high speed;
- TMS320F2812 DSP development system is comprised from circuit adaptation for input-output digital/analog buttons to simulate the functions Start/Stop to simulate inputs and digital potentiometers to simulate analog input and output LEDs for viewing;

Using the D* with TMS320F2812 digital signal processor TMS320F2812 digital control and regulate the speed of electric motors has proved very effective, reducing the work required classical adjustment. Working with it is very difficult because the tools and software modules that can be used in programming, design engineers working

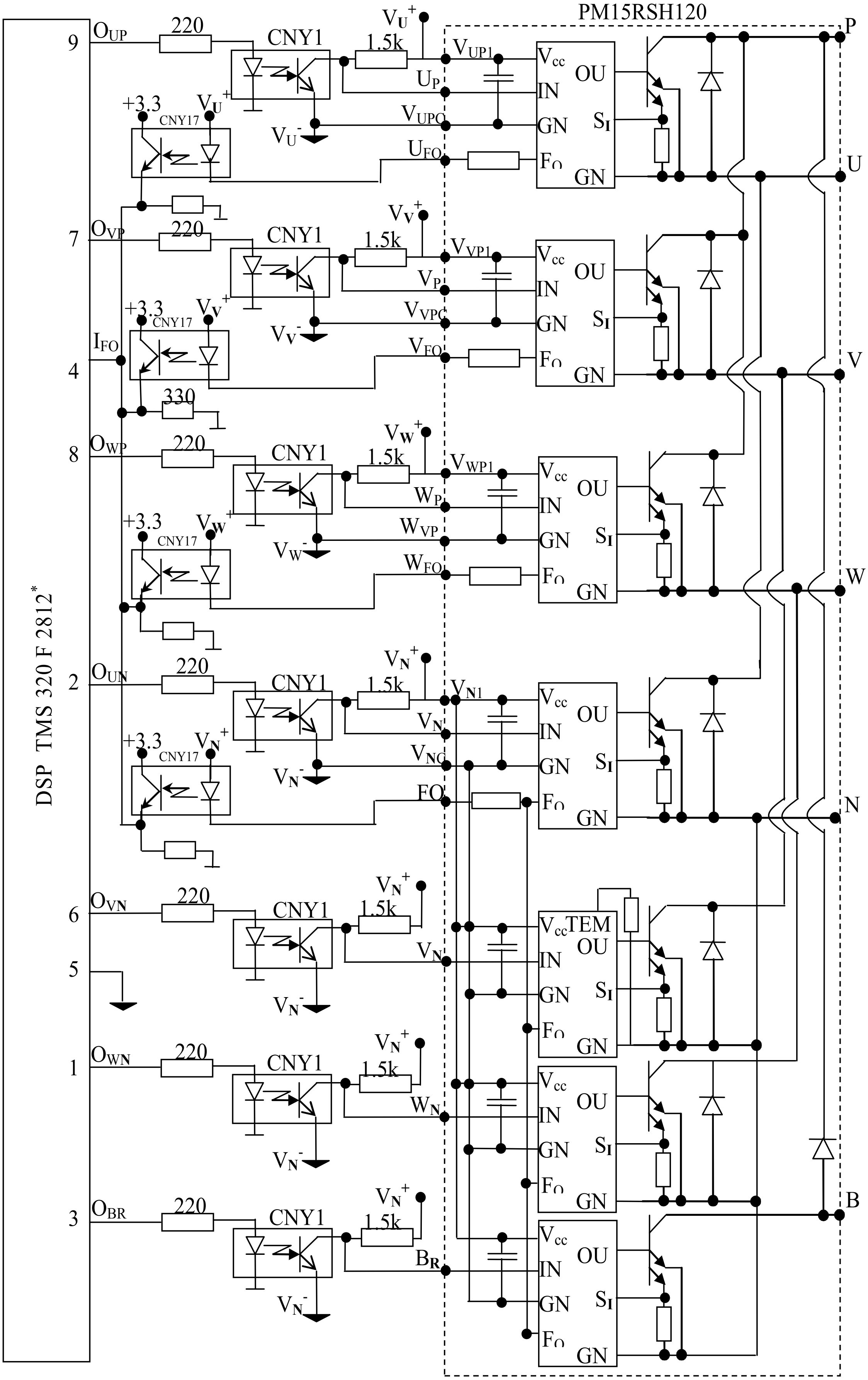


Fig. 9: The connecting intelligent power module to DSP.

minimizes the adjustment system, allowing both verification and theoretical implemantării off-line and real-time verification. F2812 has all the peripherals necessary for simultaneous control of two alternative three phase motors.

Digital signal processors can be found in medical monitoring devices in hearing aids, supercomputers or modems. Radar detectors are used in digital TVs or combine audio amplifier and laser facilities for entertainment. DSP's are actually a part of our modern existence, in translatând signals intelligence and allowing us to make decisions more precise, in a much shorter time.

Benefits of DSP processors in order utlizării electric motors are:

- Favor reducing the cost control systems in general and in particular, by eliminating the speed sensor for sensorless"structures",
- Effectively controlling the entire range of speed,
- Using control algorithms evolved reduce torque variations, resulting in lower vibration and extend life,
- Harmonic reduction by improving the default algorithms leading to cost reduction filter elements,
- Allow control after several complex variables using artificial intelligence systems (expert systems that can be found, fuzzy, artificial neural networks or genetic algorithms),
- Allow predictive maintenance through analysis and monitoring of mechanical vibration frequency spectrum with fast Fourier transform (FFT).

4 Non-linear Command in the Continuous Current Motor

The mathematical model of a process with concentrated parameters consists in a set of differential equationswe are goins to present as state equations. A linear model with constant coefficients and a reasonable degree of complexity can be determined for numerous processes and can be controlled via classical automation theories.

When the process is non-linear – however, with sufficiently regular non-linearities – a tangent linear model can be determined in each point, which enables command computation when the functioning domain is restricted (the case of regulation).

Nevertheless, there are situations when it is impossible to accurately represent process behavior in a linear model for the whole functioning domain. The following possibilities exist for such cases:

- maintain the linear command law and check its *robustness* regarding the model structure and parameters;
- designing and implementing command algorithms able to allow for system non-linearities, a method also known as *exact linearization*;
- using other command strategies: robust controls, multi-model controls, auto-adaptive controls.

Methods relying on exact linearization of non-linear systems and input-output decoupling are presented here. Discussing the issue of systems input-output decoupling is also motivated by practical reasons: it allows easier determination of the global command system and answers to systems security imperatives by isolating command paths.

Next we will show how a linearly behaving input-output system can be obtained by using a non-linear command and a change of variable (the entry is modified).

Let us consider the system:

$$\begin{cases} \dot{x} = f(x) + g(x)\cdot u \\ y = h(x) \end{cases} \tag{7'}$$

The issue is: given a point x^0, find a reaction (if possible) in a vicinity V of x^0:

$$u = \alpha(x) + \beta(x)\cdot v \tag{8}$$

defined on V and a coordinates transformation $z=\Phi(x)$ also defined on V so that the corresponding closed loop system

$$\dot{x} = f(x) + g(x)\cdot\alpha(x) + g(x)\beta(x)\cdot v \tag{9}$$

in coordonates $z=\Phi(x)$ should be linear and controllable.

In other words, let us consider the non-linear system:

$$\begin{aligned} &\dot{x} = f(x) + g(x)\cdot u \\ &y = h(x) \end{aligned} \tag{10}$$

having relative order r in a point x^0.

The state reaction:

$$u = \alpha(x) + \beta(x)\cdot v \tag{11}$$

transforms this system into one whose input-output behavior is identical to the one of a linear system having a transfer function:

$$H(s) = \frac{1}{s^r} \tag{12}$$

5 Applications of Exact Linearization by Reactions in Continuous Current Drives

The mono-variable case. The state equations attached to the regulation system are:

$$\begin{cases} \dfrac{di}{dt} = -\dfrac{R}{L}\cdot i - \dfrac{k_e\cdot\varphi_{ex}}{L}\cdot\omega + \dfrac{U}{L} \\ \dfrac{di_{ex}}{dt} = \dfrac{U_{ex}}{L_{ex}} - \dfrac{R_{ex}}{L_{ex}}\cdot i_{ex} \\ \dfrac{d\omega}{dt} = \dfrac{k_m\cdot\varphi_{ex}}{J}\cdot i - \dfrac{M_r}{J} \end{cases} \tag{13}$$

But, in this way, the equation system becomes:

$$\begin{cases} \dfrac{di}{dt} = -\dfrac{R}{L}i - \dfrac{k_e\cdot L_{ex}\cdot i_{ex}}{L}\cdot\omega + \dfrac{U}{L} \\ \dfrac{di_{ex}}{dt} = \dfrac{U_{ex}}{L_{ex}} - \dfrac{R_{ex}}{L_{ex}}\cdot i_{ex} \\ \dfrac{d\omega}{dt} = \dfrac{k_m\cdot L_{ex}\cdot i_{ex}}{J}\cdot i - \dfrac{M_r}{J} \end{cases} \tag{14}$$

If we note:

$$x_1 = i \qquad x_2 = i_{ex} \qquad x_3 = \omega \qquad \begin{cases} \dot{x}_1 = -\dfrac{R}{L}\cdot x_1 - \dfrac{k_e\cdot L_{ex}}{L}\cdot x_2\cdot x_3 + \dfrac{U}{L} \\ \dot{x}_2 = \dfrac{U_{ex}}{L_{ex}} - \dfrac{R_{ex}}{L_{ex}}\cdot x_2 \\ \dot{x}_3 = \dfrac{k_m\cdot L_{ex}}{J}\cdot x_1\cdot x_2 - \dfrac{M_r}{J} \end{cases} \tag{15}$$

The previous equation system can be written in the following form:

$$\dot{x} = f(x) + g(x)\cdot u \tag{16}$$

where:

$$f(x) = \begin{bmatrix} -\dfrac{R}{L}\cdot x_1 - \dfrac{k_e\cdot L_{ex}}{L}\cdot x_2\cdot x_3 \\ \dfrac{U_{ex}}{L_{ex}} - \dfrac{R_{ex}}{L_{ex}}\cdot x_2 \\ \dfrac{k_m\cdot L_{ex}}{J}\cdot x_1\cdot x_2 - \dfrac{M_r}{J} \end{bmatrix}$$

$$g(x) = \begin{bmatrix} \dfrac{1}{L} \\ 0 \\ 0 \end{bmatrix} \tag{17}$$

The non-linear command is thus calculated:

$$\begin{gathered} u = \alpha(x) + \beta(x)\cdot v \\ \alpha(x) = -\Delta^{-1}(x)\cdot\Delta_0(x) = \\ = -\frac{u_{ex}\cdot x_1\cdot L}{L_{ex}\cdot x_2} + \frac{R_{ex}\cdot L\cdot x_1}{L_{ex}} + R\cdot x_1 + k_e\cdot L_{ex}\cdot x_2\cdot x_3 + \frac{\dot{M}_r\cdot L}{k_m\cdot L_{ex}\cdot x_2} \end{gathered} \tag{18}$$

$$\beta(x) = \Delta^{-1}(x) = \frac{J\cdot L}{k_m\cdot L_{ex}\cdot x_2}$$

Next, the vector fields are determined:

$$\begin{gathered} \tilde{f}(x) = f(x) + g(x)\cdot\alpha(x) \\ \tilde{g}(x) = g(x)\cdot\beta(x) \end{gathered} \tag{19}$$

$$\tilde{g}(x) = \begin{bmatrix} \dfrac{1}{L} \\ 0 \\ 0 \end{bmatrix}\cdot\frac{J\cdot L}{k_m\cdot L_{ex}\cdot x_2} = \begin{bmatrix} \dfrac{J}{k_m\cdot L_{ex}\cdot x_2} \\ 0 \\ 0 \end{bmatrix}$$

$$\tilde{f}(x) = \begin{bmatrix} \dfrac{R_{ex}\cdot x_1}{L_{ex}} - \dfrac{u_{ex}\cdot x_1}{L_{ex}\cdot x_2} + \dfrac{\dot{M}_r}{k_m\cdot L_{ex}\cdot x_2} \\ \dfrac{U_{ex}}{L_{ex}} - \dfrac{R_{ex}}{L_{ex}}\cdot x_2 \\ \dfrac{k_m\cdot L_{ex}}{J}\cdot x_1\cdot x_2 - \dfrac{M_r}{J} \end{bmatrix}$$

In the new coordinates the systembecomes:

$$\begin{cases} \dot{x} = \tilde{f}(x) + \tilde{g}(x)\cdot v \\ y = \omega \end{cases} \tag{20}$$

where v is the new entry of the system.
The equation system can also be written as follows:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} \dfrac{R_{ex}\cdot x_1}{L_{ex}} - \dfrac{u_{ex}\cdot x_1}{L_{ex}\cdot x_2} + \dfrac{\dot{M}_r}{k_m\cdot L_{ex}\cdot x_2} \\ \dfrac{U_{ex}}{L_{ex}} - \dfrac{R_{ex}}{L_{ex}}\cdot x_2 \\ \dfrac{k_m\cdot L_{ex}}{J}\cdot x_1\cdot x_2 - \dfrac{M_r}{J} \end{bmatrix} + \begin{bmatrix} \dfrac{J}{k_m\cdot L_{ex}\cdot x_2}\cdot v \\ 0 \\ 0 \end{bmatrix} =$$

$$= \begin{bmatrix} \dfrac{R_{ex}\cdot x_1}{L_{ex}} - \dfrac{u_{ex}\cdot x_1}{L_{ex}\cdot x_2} + \dfrac{\dot{M}_r}{k_m\cdot L_{ex}\cdot x_2} + \dfrac{J}{k_m\cdot L_{ex}\cdot x_2}v \\ \dfrac{U_{ex}}{L_{ex}} - \dfrac{R_{ex}}{L_{ex}}\cdot x_2 \\ \dfrac{k_m\cdot L_{ex}}{J}\cdot x_1\cdot x_2 - \dfrac{M_r}{J} \end{bmatrix} \tag{21}$$

Next, the newly obtained system is checked for linearity.

$$\begin{gathered} y = \omega = x_3 \\ \dot{y} = \dot{x}_3 = \frac{k_m\cdot L_{ex}}{J}\cdot x_1\cdot x_2 + \frac{M_r}{J} \\ \ddot{y} = \ddot{x}_3 = \frac{k_m\cdot L_{ex}}{J}\cdot\dot{x}_1\cdot x_2 + \frac{k_m\cdot L_{ex}}{J}\cdot x_1\cdot\dot{x}_2 - \frac{\dot{M}_r}{J} = \end{gathered} \tag{22}$$

Therefore,

$$\ddot{y} = v \tag{23}$$

which means that the system with the new coordinates (v-input şi ω- output) is linear.
In order to obtain high performance,new v must be:

$$v = k_1\cdot(\omega_{ref} - \omega) - k_2\cdot\dot{\omega} \tag{24}$$

where k_1, k_2, are coefficients obtained by poles allotting technique, and they can have the form:

$$\begin{gathered} k_1 = \omega_0^3 \\ k_2 = 2{,}466\cdot\omega_0^2 \end{gathered} \tag{25}$$

ω_0 being pulsation of break in an open circuit.
An example of scheme for such a system is presented in Fig. 10.

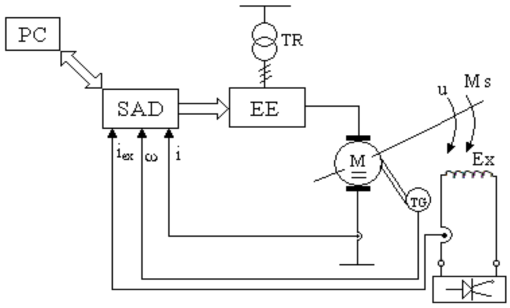
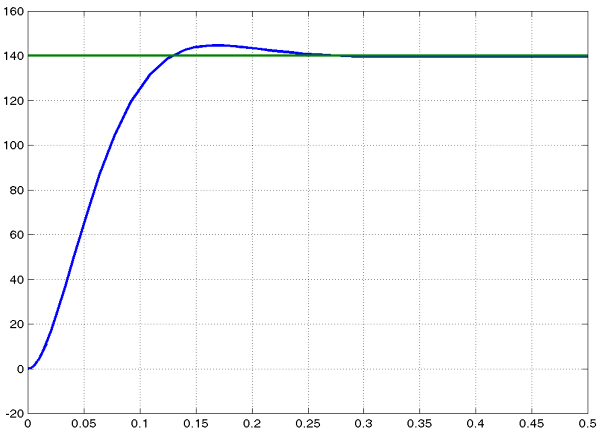
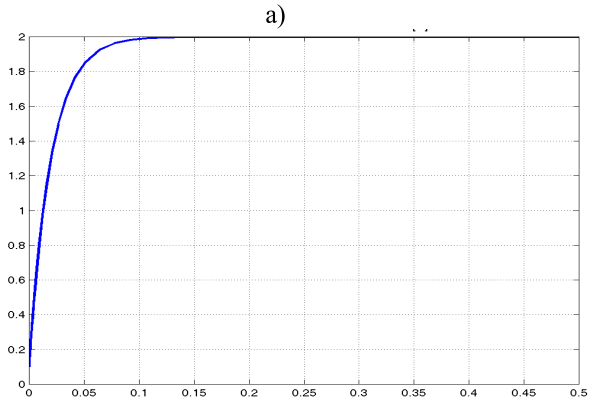


Fig. 10: Mechanical characteristics of the asynchronous motor.

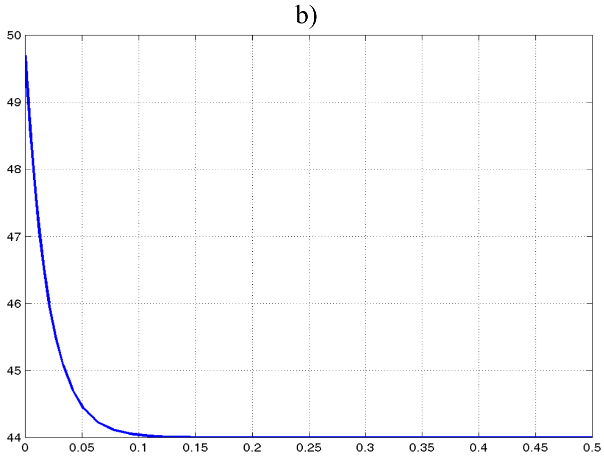
Fig 11 illustrates the results of simulating drives functioning system in the case of using the non-linear command.



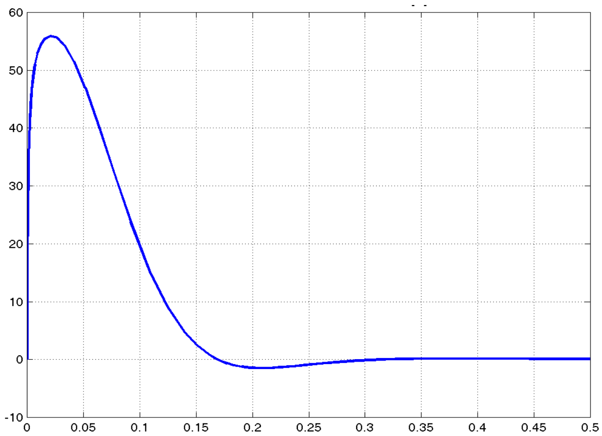
a)



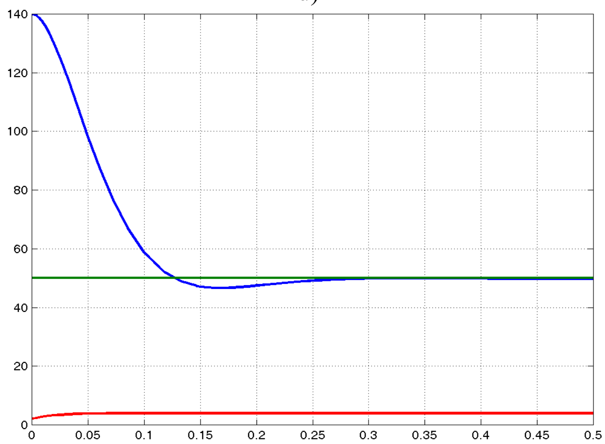
b)



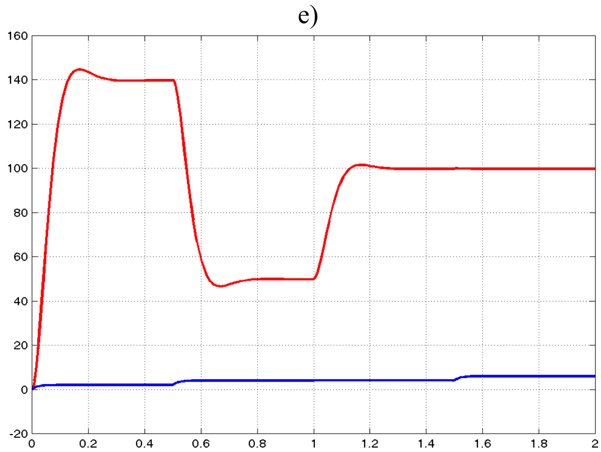
c)



d)



e)



f)

Fig. 11: Simulation results in the case of the non-linear command.

6 Conclusions

The relative order r of a linear system can be interpreted as being the excess poles-zeros of the transfer function.

A linear system was shown to be obtained from a non-linear system if a non-linear command and a change of coordinates are used.

In practice, for implementing this command algorithm, it is absolutely necessary that we should have a data acquisition system enabling: acquisition of the values in the state vector as well as the input and output in the regulation system, together with non-linear command computation and command elaboration by the execution element.

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