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A comparative study of performance of AC and DC electric drive control systems with variable moment of inertia

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ABSTRACT

In electric drive control systems, the main goal is to maintain the driving motor speed to meet the mechanism's requirements. In some practical industrial applications the mechanically-coupled load to the motor shaft has a varying mass during the system operation. Therefore, the change of mass changes the value of the moment of inertia of the system. The moment of inertia impacts the system operation, particularly the transient performance. Therefore, the variation of moment of inertia on the motor shaft during its operation creates additional challenges to accomplish a high-quality speed control. The main purpose of the current work is to study the impact of the variation of moment of inertia on the performance of both AC and DC electric drive control systems and to make a comparison between them. A mathematical analysis and simulations of the control system models had been presented; one time with three-phase induction motor and another time with DC motor, both with variable moment of inertia. A simulation of both systems had been accomplished using the Simulink software in MATLAB. The simulation results of operation of these systems have been analysed in order to get useful conclusions and recommendations for the electric drive control system designer.

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1. INTRODUCTION

The ac electric-drive control systems, nowadays, are used in almost all industrial applications more than the DC-motor systems [1]. About four decades ago the asynchronous motors (induction motors) have been operated under a fixed-frequency speed directly from the grid. Later, with the development of the power-electronic devices, circuits and their capabilities, these machines had become able to operate with adjustable frequency-speed through power-electronic converters. Using variable speed motor drive with open loop may offer a satisfied performance at steady state conditions without need of speed regulation for some applications. But, in the cases where the drive system requires fast dynamic response and accurate speed, the open loop control becomes unsatisfactory. Therefore, it is necessary to operate the motor in a closed-loop mode.

Although, both of these AC and DC electric drive control systems still may be found in use. Many researchers paid attention to the DC and the AC electric machines [2]. Many of them studied the DC-motor drives and their control [3-8]. Latha [8] studied the design of a model reference adaptive speed control of brushless DC-motor drive. Ayyar *et al.* [7] paid attention to the design of the speed controller of converter fed DC-motor drive using model order reduction technique.

Usually, the design of control system components to get high performance behavior, for high-order systems, involves serious computational difficulties and ponderous tasks. Therefore, for such systems there is a need in designing of high requirements controllers through suitable order-reduction of the model [9-13]. In the works [9-13], authors studied different electric-drive control systems and designing different controllers. Al-Abbas [14] studied a reduced order of high order control systems. In [1, 15-20] an electric-drive control system with asynchronous motor had been analyzed. Addasi [21] presents a study of increasing moment of inertia of a DC-motor control system.

The main problem in all the above mentioned researches is that: they did not make enough study and comparison between the DC and the AC electric-drive control system performance, particularly under the challenges of changing the moment of inertia during their operation. They did not study the effect of the change, including the step-change, of the moment of inertia of the mechanical system. The main purpose, and the contribution, of this paper is to produce a mathmodel, to simulate and analysis the results of the simulations of these different-drive control systems with smooth- and step-changing of the moment of inertia and then to make a comparison between the performance of both systems. This comparison study to be made between both systems in steady-state as well in transient operation.

2. THE MATHEMATICAL MODEL OF THE DC MOTOR AND FOR THE INDUCTION MOTOR

The mathmodel of the direct-current motor can be built on the basis of the well known equivalent circuit of the DC motor [21]. The differential equation of the voltage balance of the armature circuit may be given by the following equation:

$$V_s = E_a + R_a i_a + L_a \frac{di_a}{dt} \tag{1}$$

where: V_s is the voltage of the power supply, i_a, L_a, R_a, the motor armature current, inductance and resistance, respectively, $E_a = K_e \phi \, \omega_m$ is the back electromotive force in the armature circuit. From the mechanical dynamics of the motor, the torque equation is:

$$J \frac{d\omega_m}{dt} = T - T_L - B\omega_m \tag{2}$$

Where:
J = Total moment of inertia referred to the motor shaft, in kg.m^2
T = Driving motor torque, in N.m
T_L = Load torque, in N.m
B_{vs} = Viscous friction constant, in N.m.s

The voltage of the power supply is considered to be stable, balanced and no variation is going on. The loaded slip-ring 3-phase asynchronous motor (SRIM) can be mathematically modelled by the following five linear differential equations [22]. These state equations of the studied induction motor are expressed via flux linkages in (α, β) system of coordinates:

$$\frac{d\lambda_{s\alpha}}{dt} = v_{s\alpha} - \frac{R_s}{L_{\sigma s}} (\lambda_{s\alpha} - \lambda_{\mu\alpha}) \tag{3}$$

$$\frac{d\lambda_{s\beta}}{dt} = v_{s\beta} - \frac{R_s}{L_{\sigma s}} (\lambda_{s\beta} - \lambda_{\mu\beta}) \tag{4}$$

$$\frac{d\lambda_{R\alpha}}{dt} = \frac{R_R}{L_{\sigma R}} (\lambda_{R\alpha} - \lambda_{\mu\alpha}) - \omega \;\; \lambda_{R\beta} \tag{5}$$

$$\frac{d\lambda_{R\beta}}{dt} = \frac{R_R}{L_{\sigma R}}(\lambda_{R\beta} - \lambda_{\mu\beta}) + \omega\ \lambda_{R\alpha} \tag{6}$$

$$\frac{d\omega}{dt} = \frac{1}{J}(\tau - \tau_m) \tag{7}$$

where ω is the radian per second angular speed of the motor; $\lambda_{s\alpha}, \lambda_{R\alpha}, \lambda'_{s\beta}, \lambda'_{R\beta}$ are the flux linkages of the SRIM stator and the rotor magnetic circuits in α and β axes, respectively; $\lambda_{\mu\alpha}, \lambda_{\mu\beta}$ are the flux linkages of the magnetization branch in α and β axes, respectively; $v_{s\alpha}, v_{s\beta}$ are the voltages of the stator side in α and β axes, respectively; R_s, R_R are the resistances of the stator and rotor windings per phase, respectively; $L_{\sigma s}, L_{\sigma R}$ are the magnetic leakage inductances of the stator and the rotor circuits, respectively; J is the total moment of inertia in kg.m^2 of the system referred to the shaft of the motor, τ, τ_m are the electromagnetic driving torque of the motor and the load torque in N.m., respectively

3. THE MODEL OF THE DC AND AC ELECTRIC DRIVE CONTROL SYSTEMS

The desired specifications of any control system are usually translated in the form of a transfer function. For the industrial processes, whose performance are unsatisfactory with the reference model having the desired performance, a controller should be designed such that to meet the specifications of the overall system matching the reference model. Usually, the series controllers for high order systems are preferred over the controllers in the feedback path, that because a large number of the state variables in the control system would require large number of sensors in the feedback controller design.

In this work the series controllers were used, and the technical-optimum method (TOM) is used in designing the controllers of these control systems, which is based on the well-know and widely used PID controllers [9, 23-27]. Figure 1 illustrates the block diagram of such series-controller control system. Such a control system has two feedbacks; the feedback of the current loop (the inner loop) and the angular speed (ω) feedback (as the main loop and the outer loop). In the analyzed AC control system a slip ring 3-phase induction motor (SRIM) is used. The load of this motor is considered with increasing, during operation, moment of inertia (J) as the rotating mass is increasing. The variation of moment of inertia will be studied during both starting and the steady-state conditions.

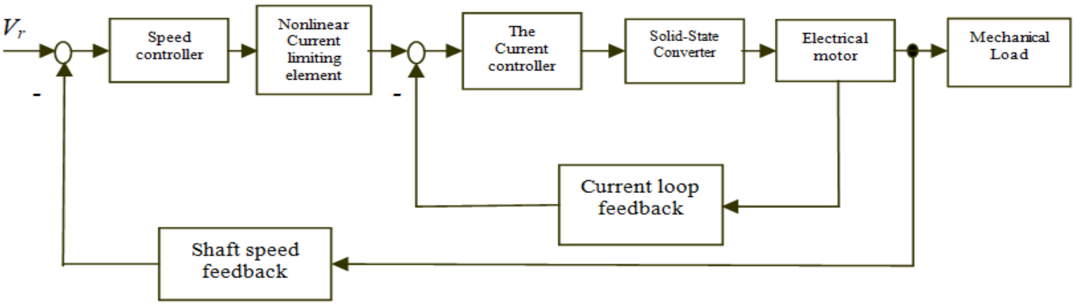


Figure 1. The general diagram of the studied control system with the two feedbacks

The considered transfer function of the both studied types of motors has a block-diagram, divided into two components: the electrical component with the armature current output and the mechanical component with angular speed output (ω). A transfer function of a first order type may describe the electrical component, which can be written:

$$G_a(s) = \frac{1/R_{a.t}}{L_a/R_a \cdot s + 1} \tag{8}$$

The gain of the mechanical component of the motor has the form: $G_m(s) = \frac{K_m}{s}$, where $K_m = K\Phi/J$. The gain of the current feedback path element:

$$K_{Ifb} = \frac{V_C}{\lambda \cdot I} \tag{9}$$

where λ is the relative (per unit) maximum starting current. By using the technical optimum method (TOM) of design, the transfer function of the series-current regulator may be written:

$$G_{Ir} = \frac{1/K_{fb,c}}{2\,G_{cl}} = K_{Ir} + \frac{1}{T_{Ir}\ s} \tag{10}$$

where K_{Ir} is the gain of the P-type controller, T_{Ir} is the time constant of the I-type current controller. The transfer function of the current closed loop, designed using the TOM technique has the following final form:

$$G_{CL,TO} = \frac{1/K_{Ifb}}{1+2T\ +2T^2\cdot s^2} \approx \frac{1/K_{fb,c}}{2T\ \cdot s+1} \tag{11}$$

Finally the series-controller of the angular speed ω, using the same method will have the transfer function:

$$G_{SR,TO} = \frac{1/K_{ifb}}{G_{or,s}\ 4T\ \cdot s\,(2T\ \cdot s+1)} \tag{12}$$

4. SIMULATION, QUALITATIVE ANALYSIS AND COMPARISON

The both of DC and AC electric drive control systems were simulated and their performance had been studied under different conditions of operation. The two systems were studied under the action of a smooth and a step changes of load and of the moment of inertia. Figure 2 shows the block diagram created in MATLAB/Simulink basing on the above presented mathmodel of the control system with DC-motor. Figure 3 illustrates the block diagram of the control system with slip-ring induction motor (SRIM). The numerical examples of these systems were produced for the simulations, using Simulink software. Every one of these case studies is applicable in many applications in industry like metal-rope winding mechanisms and paper manufacturing machinery or in textile industry, in which the moment of inertia increases during the motor rotation.

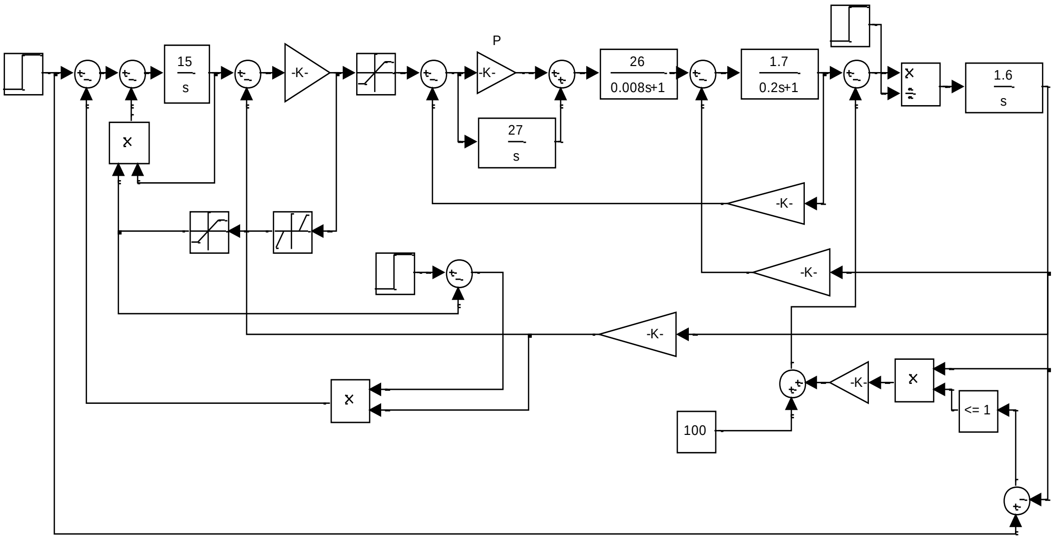


Figure 2. Block diagram of the control system with DC motor

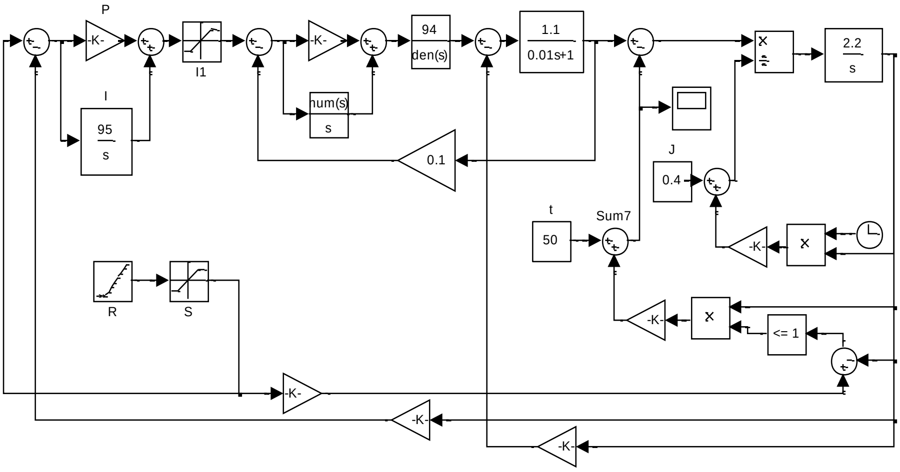
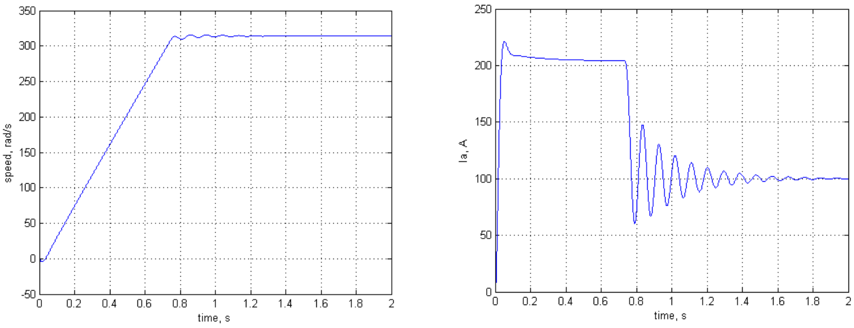


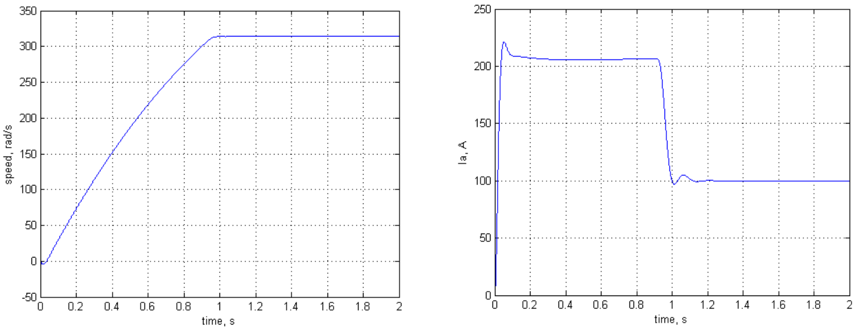
Figure 3. Block diagram of the control system with SRIM

Some results of simulations of these models are depicted in Figures 4-13. The curves in these figures present the performance of the systems during transients and the steady-state conditions of the both designed control systems at different operation conditions. Figure 4 shows the control system with asynchronous motor performance at unchanged moment of inertia (J) during its operation. Figures 5(a)-(b) illustrate the angular speed (ω) and the armature current (I) as a function of time with increasing moment of inertia (J) for the SRIM control system. An examination of this figure shows that the duration of the transient process is about 1.1 seconds, the speed overshoot is almost 0% and the steady-state error value in speed is very small, it does not reach the value of 0.05%.



(a) (b)

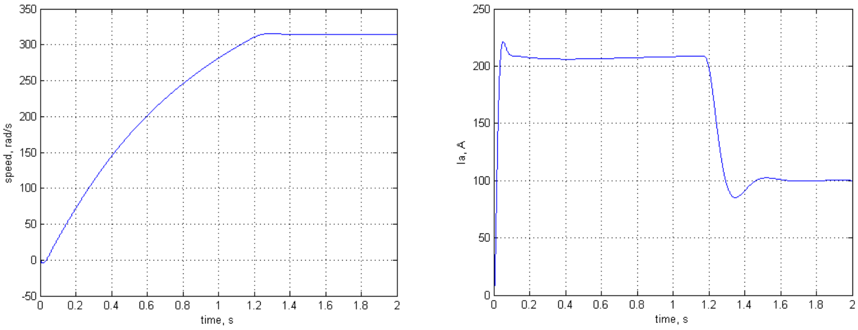
Figure 4. SRIM system performance at constant J, (a) Speed versus time, (b) Current versus time



(a) (b)

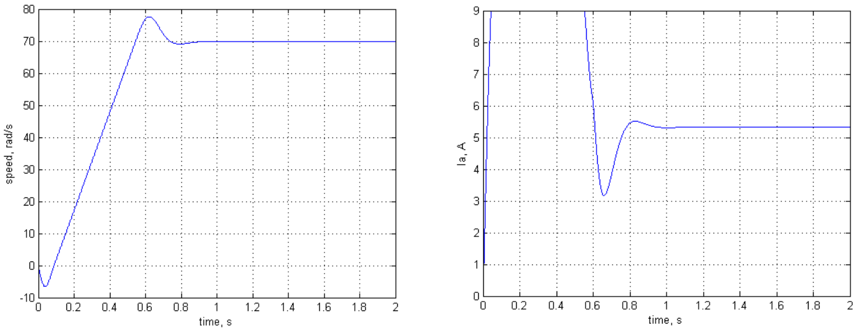
Figure 5. SRIM system performance when J was tripled during 2 seconds, (a) Speed versus time, (b) Current versus time

Figures 6(a)-(b) illustrate the angular speed ω and the armature current with variable J and load torque but at different rotating speed for the same system. The curves show that the settling time takes only 1.4 second, the overshoot of the angular speed equals 1% and the steady-state error in speed value does not overtake 0.05% of its rated value. The proposed model has been tested with a wide range of change in the load and moment of inertia (J) and the results showed high performance of the system. Figure 7 shows the performance of the control system with DC motor at constant moment of inertia (J). Figures 8(a)-(b) illustrate the angular speed ω and the armature current curves, respectively, with variable J and load torque for the DC motor system. From these curves it is noticed that the settling time extends for 1.6 second, the overshoot reaches the border of 20% and the steady state error in speed value does not exceed 0.05%.



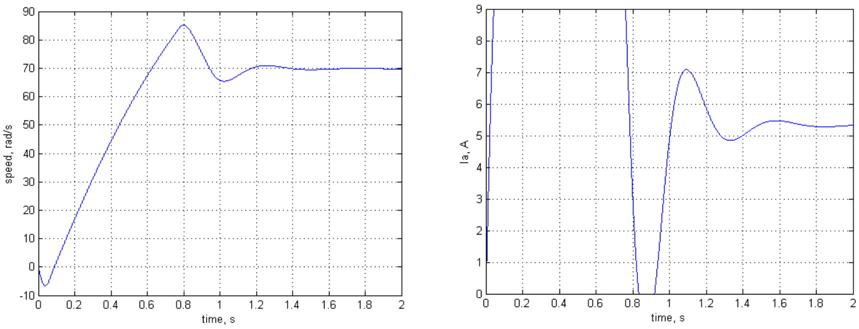
(a) (b)

Figure 6. SRIM system performance when J was increased 5 times of initial value during 2 seconds, (a) Speed versus time, (b) Current versus time



(a) (b)

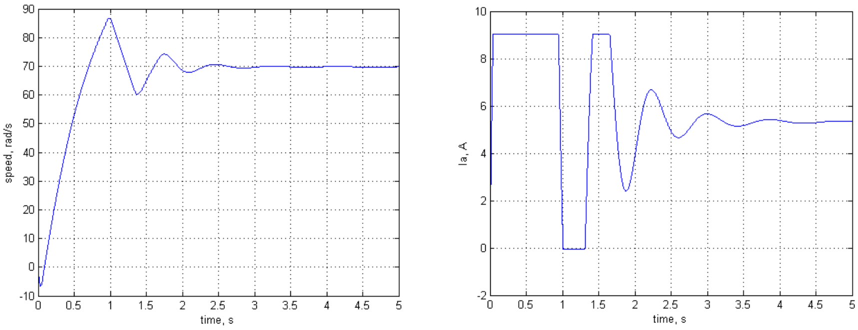
Figure 7. DC motor drive performance at constant J, (a) Speed versus time, (b) Current versus time



(a) (b)

Figure 8. DC motor drive performance when J was tripled during 2 seconds, (a) Speed versus time, (b) Current versus time

Figures 9(a)-(b) illustrate the angular speed and the current variations, respectively, with variable J and load torque but at different operating speed for the same system. The curves show that settling time takes 3 second, the speed overshoot reaches the value of 20% and the steady-state error of the angular speed value does not overstep the value of 0.05%. The proposed model has been tested with a wide range of change in the load and moment of inertia (J) and it showed high performance of operation. By comparing the performance of the AC and the DC motor systems it may be mentioned that in steady-state operation both of them, almost, have the same high accuracy. In the other hand, the transient time duration and the overshoot values of the angular speed of the SRIM system has much better performance.

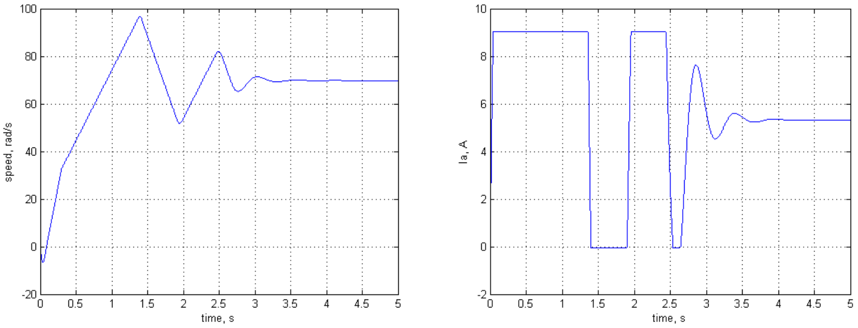


(a) (b)

Figure 9. DC motor system performance when J was increased 5 times of initial value during 2 seconds, (a) Speed versus time, (b) Current versus time

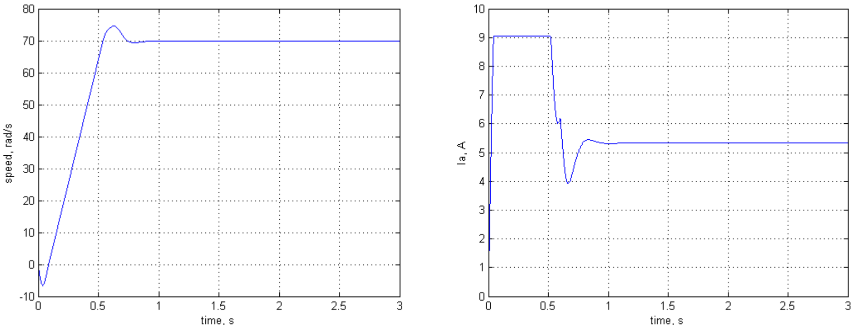
In Figures 10-13 are depicted the system angular speed ω and the armature current curves for the both systems with step change of moment of inertia during starting time or after. Figure 10 shows that the performance of the SRIM control system with step change of J during starting, where J was increased three times of its initial value at the time of 0.3 second of the starting. The figure shows that the settling time takes 3.8 second and the speed overshoot value reaches a higher value (about 28%), which is sufficiently larger if compare with the case of (J) step-change occurring after reaching the steady state. Figure 11 shows that the performance of the SRIM with step change of J just after starting, where the J was increased three times of its initial value at the instant of 1.2 second after starting. The figure shows that this change, almost, has no effect on the system performance.

Figures 12 and 13 illustrate the DC-motor system performance with step change of J during starting or after reaching the steady state. Figure 12 shows that the performance of the DC motor drive with a step change of J during starting, where it was increased three times of its initial value at the instant of 0.3 second after starting. The curves in this figure show that the settling time does not exceed 1.8 second and the speed overshoot is limited to 4%. Figure 13 shows the performance of the DC motor drive with step change of J just after starting, where moment of inertia was tripled at the instant of 1.2 second after starting. Curves in this figure show that this change, almost, has no effect on the system performance.



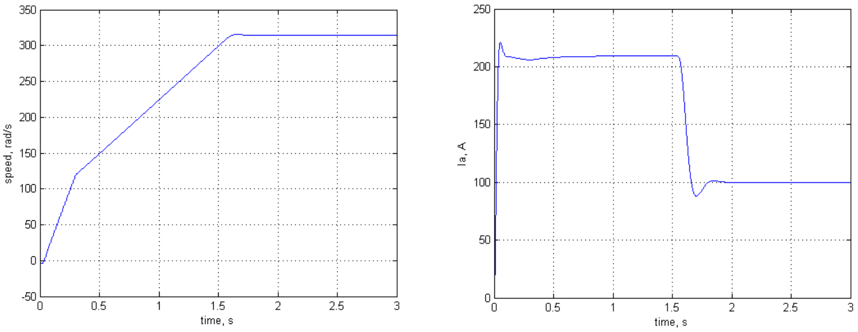
(a) (b)

Figure 10. SRIM system performance with step change of J during starting (3 times at 0.3 sec), (a) Speed versus time, (b) Current versus time



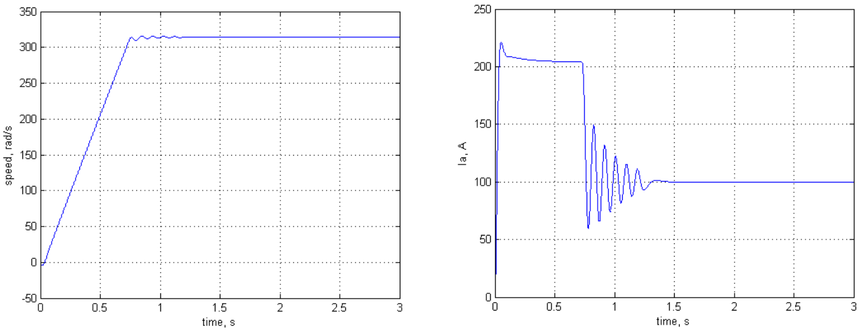
(a) (b)

Figure 11. SRIM system performance with step change of J just after starting (3 times at 1.2 sec), (a) Speed versus time, (b) Current versus time



(a) (b)

Figure 12. DC-motor system performance with step change of J during starting (3 times at 0.3 sec), (a) Speed versus time, (b) Current versus time



(a) (b)

Figure 13. DC-motor system performance with step change of J just after starting (3 times at 1.2 sec), (a) Speed versus time, (b) Current versus time

By examining the results of the simulations and comparing the performance of the SRIM- and the DC-motor systems, as shown in Table 1, it may be noticed that in steady-state both of the studied systems, have the same (or similar) high accuracy (same steady state error). In the other hand, the settling time and the overshoot of the angular speed characteristics of the SRIM system is better than (smaller) the DC-motor system operation except in case of step change of moment of inertia J during starting time. But this step change during starting time is not real in practical applications. Therefore, the SRIM control system behaves better than the DC one.

Table 1. Comparing the performance of the AC and the DC motor control systems

The change of moment of inertia (J)	Settling time in seconds		Overshoot (%)		Steady state error, less than	
	DC motor system	Induction motor system	DC motor system	Induction motor system	DC motor system	Induction motor system
Constant moment of inertia (J)	0.9	1.1	10	1	0.05%	0.05%
$J_2 = 3J_1$ after starting	1.6	1.1	20	0	0.05%	0.05%
$J_2 = 5J_1$ after starting	3	1.4	20	1	0.05%	0.05%
$J_2 = 3J_1$ during starting	1.8	3.8	4	28	0.05%	0.05%

5. CONCLUSION

A mathematical model for the dynamic operation of both AC and DC electric drive control systems, based on the technical optimum method technique, had been built. A simulation of both system models had been produced using the powerful MATLAB software. The effect of the variation of moment of inertia on the performance of both SRIM-and DC-motor control systems had been studied. Then a comparison analysis between the two systems had been presented. The results of the simulations for both systems confirm that the two designed models satisfied the required high performance of the control system in both steady state and transients, even with step change of the moment of inertia. By comparing the performance of the studied AC and DC motor systems it may be mentioned that in steady-state operation both of them have the same high accuracy. They have a very small steady state error. In case of smooth or step increasing of the moment of inertia J, the SRIM system has better performance. The overshoot of the angular speed in the SRIM does not exceed the value of 1%, while for the DC-motor system it reaches 20%. The required settling time is small enough for both models, but still better for the SRIM system. In the other hand, the settling time and the overshoot of the angular speed characteristics of the SRIM were increased by a larger amount comparing to the DC-motor system, in the case of step change of the moment of inertia during the starting, but this is not substantial as this abrupt change during starting time is not real in practical applications.

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BIOGRAPHIES OF AUTHORS

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