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Speed synchronization of two DC motors with independent loads based on the higher load torque

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ABSTRACT

Dual-motor and multi-motor electric drive systems have been used in many industrial applications, and speed synchronization of the motors can always get worse by system parameter uncertainties and load torque perturbations. This work focuses on the application of adjustable speed double-direct current (DC) motor drive control systems. In this paper, a system of two DC motors with armature control at different load conditions has been built. The synchronization of these motors was set basing on the higher torque of the two motor shafts. When two DC motors operate at different shafts a challenge appears in synchronization of their speeds, particularly with the existence of load difference allocated on their shafts. This work paid special attention to this problem. It presents a dynamic simulation of speed control and synchronization of dual DC motor drive. The results show the advantages of the used technique in terms of steady-state and transient performance.

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1. INTRODUCTION

In many industrial applications such as surface mounting technology machines, different types of cranes, and computer numerical control machines the load is driven by, at least, two motors. In such applications all driving motors are arranged to track the desired trajectories by keeping their speed the same. Although identical driving equipment would be selected, the motors synchronization can always be deteriorated by the variations of the drive system parameters particularly the load torque values at different shafts. Poor synchronization accuracy will decrease the quality of operational performance. Hence, with the increasing demand for high accuracy and high-speed response, controlling multi-motor electric drive system to achieve good synchronization performance while there are various disturbances has become a great challenge in the modern industrial applications.

Many works studied the multi-motor drive systems [1]–[10]. The researchers [2], [4] used the fuzzy control for speed synchronization of the motors. Torres *et al*. [6] studied a multi-induction motor robot. Regardless of the widespread use of ac machines in industry and various applications [11]–[13], direct current (DC) machines still find their way to use in many applications. In the works [7], [14], [15] attention is paied to speed control of multiple synchronous motors. Different such problems of the DC motor drive systems are presented in the papers [16], [17]. In the current years, both the induction motors and the DC motors are used in drive systems [18]–[24]. Even the synchronization of the single-phase induction motors may be met in some works [25].

In the last decades the induction motor dominates in industrial applications as it has higher efficiency, less cost and lower maintenance. But the DC motors still in use in many applications such as multi-motor systems due to their simple and very good speed control features [26]. Abu-Ghazal and Jaber [27] present a comparative analysis of induction motor and interior permanent magnet synchronous motor. Tabet *et al*. [28] paid attention to the induction motor starting and control. But studies of the DC multi-motor systems still suffer some lack. Therefore, in the current work attention has been paid to this issue. The speed of DC motor is directly proportional to the armature voltage and inversely proportional to the flux of the field winding. In DC motor drives with armature control the desired speed is obtained by varying the armature circuit voltage. In our study in this work, two DC motors with armature circuit voltage control will be considered.

2. MODELING OF THE ARMATURE CONTROL OF SEPARATELY EXCITED DC MOTOR

A separately excited DC motor has been used as the actuator of the drive system. The speed control of the motor is achieved via the armature circuit. The armature-controlled DC motor speed control system is shown in Figure 1. Modeling of any electrical machine starts with the real machine, because it is necessary to determine its parameters. After that motor model can be created by using a mathematical model that describes the motor.

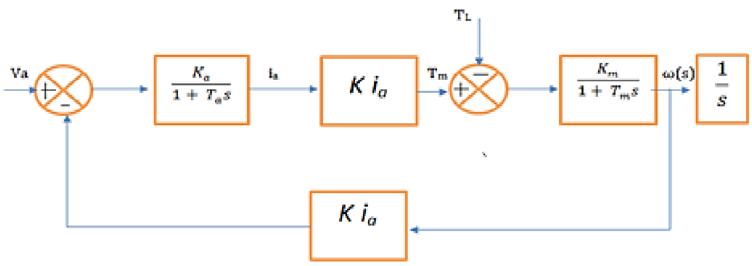

Figure 1. DC motor armature control block diagram

Basing on the mathematical model, simulation model can be made using the well-known software MATLAB/Simulink. The motor performance in steady state and transient can be obtained from the known motor model, and the required equations are given. The DC motor is, actualy, a torque transducer. The torque developed at its shaft is directly proportional to the magnetic field flux and the current in the armature circuit. Since the separately excited DC motor is extensively used in electric drive control systems, it is necessary to create a mathematical model for its control. Then a suitable design criterion has been used. It is assumed that the magnetic saturation is ignored; thus, the basic torque and emf motor equations are:

$$T = Kf\ If\ Ia = Km\ Ia \tag{1}$$

$$ea = Kf\ If\ \omega m = Km\omega m \tag{2}$$

where K_m=K_f I_f is a constant that depends on the motor construction.
The Laplace transformations of (1) and (2) are:

$$T(s) = Km\ Ia\ (s) \tag{3}$$

$$Ea\ (s) = Km\ \omega m(s) \tag{4}$$

Just after the power supply is switched on (at t=0) the voltages balance equation will be as (5):

$$Va = ea + Ra\ Ia + La\ (dIa/dt) \tag{5}$$

From (2) and (5):

$$Va = Km\ \omega m + Ra\ Ia + La\ (\mathrm{dIa/dt}) \tag{6}$$

Laplace transform of (6) at zero initial condition is:

$$Va(s) = Km\,\omega m(s) + Ra\,Ia(s) + La(s)\,Ia(s) \quad (7)$$

$$Va(s) = Km\,\omega m(s) + Ia(s)\,Ra\,(1 + s\,\tau a) \quad (8)$$

where $\tau a = La/Ra$ is the time constant of the armature circuit. The dynamic equation of the torques balance for the mechanical part is:

$$T = J\,d\omega/dt + B\omega m + TL \quad (9)$$

The term (B ω_m) represents the rotational loss torque (Viscus Friction) of the system. The Laplace transform of the motion (9) may be rewritten as (10):

$$T(s) = J\,s\,\omega m(s) + B\,\omega m(s) + TL(s) \quad (10)$$

From (3) and (10) we get:

$$\omega m(s) = (Km\,Ia(s) – TL(s))/(B\,(1 + s\,\tau m)) \quad (11)$$

where τ_m=J/B is the time constant of the mechanical part of the system.
From (4) and (8) we get:

$$Ia(s) = (Va(s) – Km\,\omega m(s))/(Ra\,(1 + s\,\tau a)) \quad (12)$$

The transfer function of the system in (s) domain may be written as (13):

$$\omega m(s)/V(s) = [(K/Ra\,B)]/[(1 + s\,\tau m)\,(1 + s\,\tau a)] \quad (13)$$

Basing on the mathmodel, Figure 1 presents the block diagram of the DC motor with armature control. In (13) is the required transfer function of the studied control system. One of the used ways of getting variable armature voltage is by connecting a variable resistance in series in the armature circuit. Armature controlled direct current motors offer a very good accuracy and a wide range of speed variation.

3. MODELLING AND SIMULATION OF THE SEPARATELY EXCITED DUAL DC MOTOR WITH ARMATURE CONTROL

Speed control of DC motor with separately excitation and performance analysis using MATLAB/Simulink has been done. By simulating one motor with armature control and set the parameters of that motor, while keeping the field voltage of the motor constant. The following parameters, in Table 1, for the motor were used.

Table 1. Physical parameters of SEDM

Parameters of SEDM	Values
Armature resistance (Ra)	0.5 Ω
Armature inductance (La)	0.1 H
The rotor moment of inertia (J)	5 kg.m^2
Damping ratio (B)	0.01 N.ms
Electromotive force constant (KΦ)	1.6 Nm/A

In this work the armature control has been used. Using specific controller, the reference value of this control system can be expressed as speed or as voltage, so in MATLAB simulation we will set up the reference value as step input of speed as a function of constant power over variable load torque. Among different types of controllers, the proportional integral derivative (PID) controller is relatively simple in terms of its implementation and the way it works. The PID controller is used to control the speed of the motor in the studied system. Various combinations of PID, proportional K_p, integral K_i, differential Kd, is applied to run tests and observe the response of the system. Figure 2 shows the block diagram for conventional PID controller and Figure 3 shows the block diagram of the closed loop system with PID controller. Implementation of the DC motor control system with the same parameters has been done twice: one time with PID controller and the other time without the PID controller with the same reference input. We can see the difference by comparing the performance for both systems.

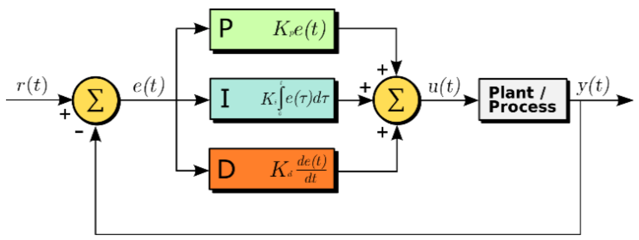

Figure 2. The block diagram of the PID controller

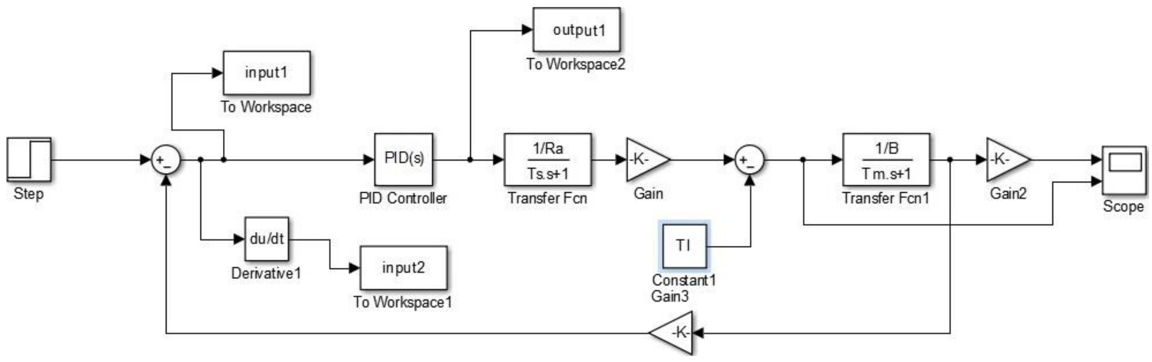

Figure 3. The DC motor armature with PID controller

4. RESULTS AND DISCUSSION

Figure 4 represents the output response of the system without PID controller with reference input as speed of 1000 rpm. To enhance the performance of the system by adding PID controller, it is needed to set proper parameters for the controller, this process is called parameter tuning. This could be achieved by using different methods. Tuning of PID controller parameters is done by setting the reset time to a high value and the rate to zero and increasing the gain until the oscillations in the loop occurs at a constant amplitude. Then set the gain of the PID controller to the half of that value and adjust the reset time so it corrects for any offset within an acceptable short time. Finally, increase the rate of the PID controller loop until the overshoot decreased to acceptable value.

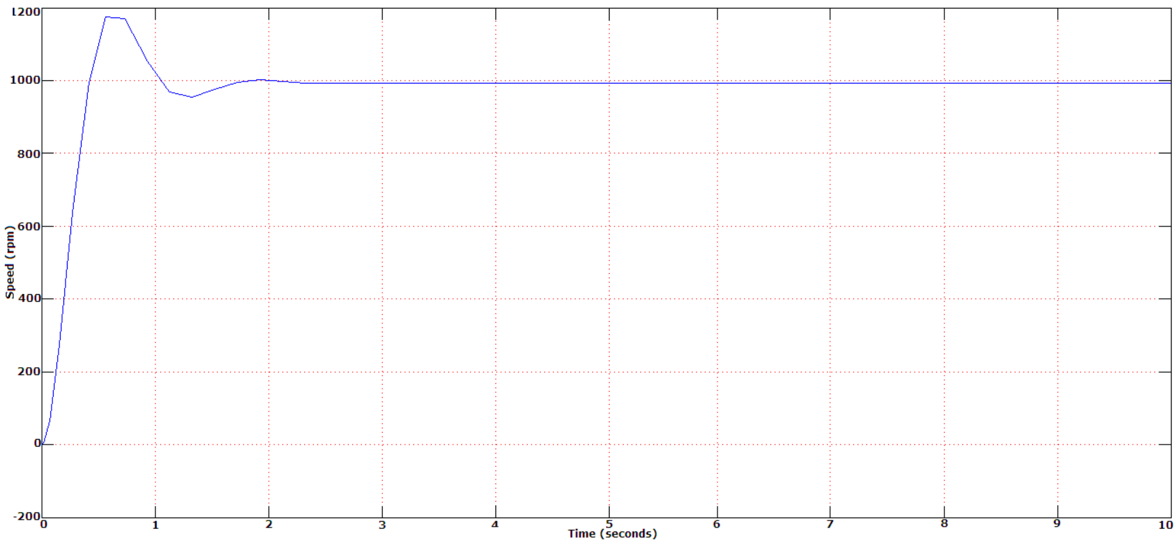

Figure 4. Armature control without PID controller

MATLAB PID controller block can automatically find the PID parameters based on how much robust and how fast the system response is. After performing the parameters tuning, these values are depicted in the Table 2. Figure 5 represents the output response of the system with PID controller with reference input as speed of 1000 rpm.

Table 2. PID parameters for DC motor armature control

PID parameters	The value
K_p	2.05991
K_i	0.22679454
Kd	0.42291363

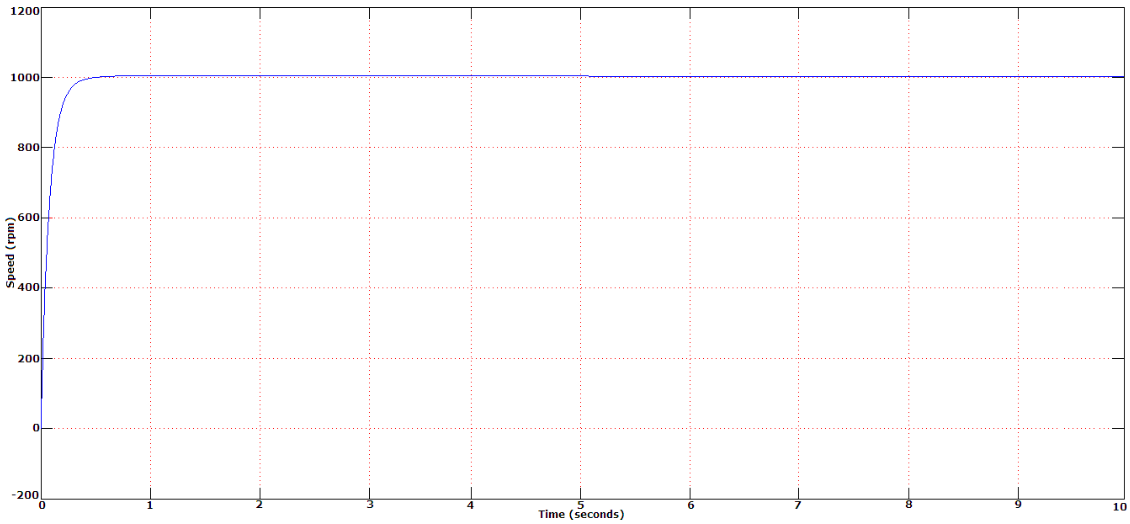

Figure 5. Armature control with PID controller

By making a comparison, in terms of overshoot, settling time, raise time and steady state error, between the response without PID controller shown in Figure 4 and the response with the PID controller shown in Figure 5, Table 3 will summarize this comparison. Figure 6, also, shows both responses in the same time interval. From this table of comparison, it is easy to note that the system with tuned parameters PID controller has much better performance.

Table 3. System characteristics with and without PID

Performance characteristic	PID	Without PID
Ts	1.2 sec	3.25 sec
Tr	0.216 sec	0.486 sec
P.O. %	.016%	19.26%
e.s.s	11*e-5	0.015

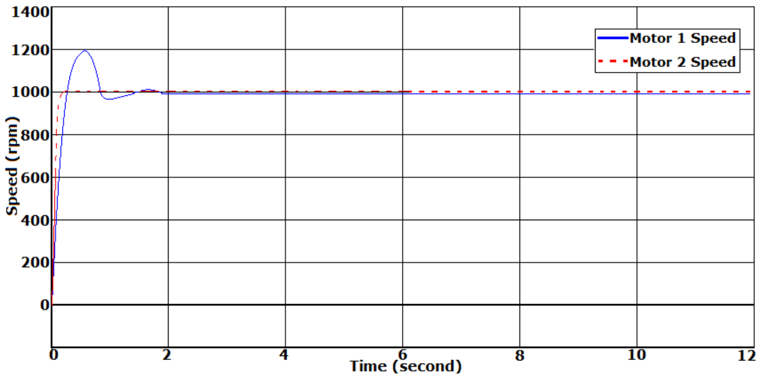

Figure 6. Armature control (PID vs without PID)

After finding the proper parameters for the PID controller the two-armature control DC-motor systems with the same parameters had been built. The synchronizing method between them is simple: the input of both systems is the speed as a function of constant rated power and load torque which is variable. The input must be equal for both systems to achieve synchronizing, and since there are two motors with different loads, the system will pick the motor with the higher load torque. The switch block in the simulation is a basic logic; it makes simple comparison between load torques of both motors and set the higher one as a reference value (since the power is constant it can be divided by reference torque that gives the speed reference value). Figure 7 represents the simulation block diagram of this system. Figures 8 and 9 show the variation in torque for motor 1 and motor 2 respectively.

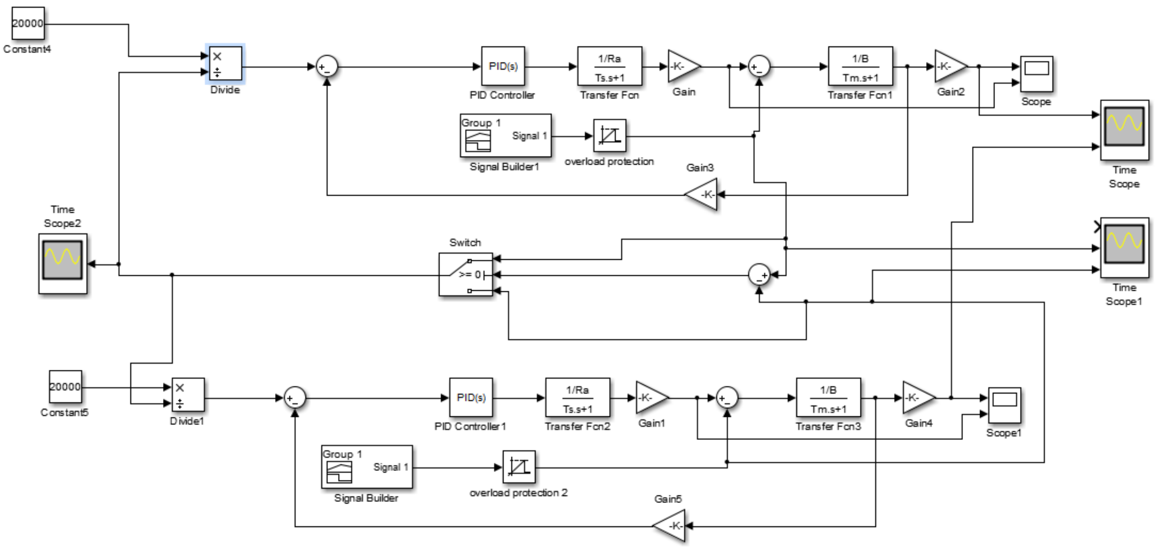

Figure 7. DC motors synchronizing based on load torque

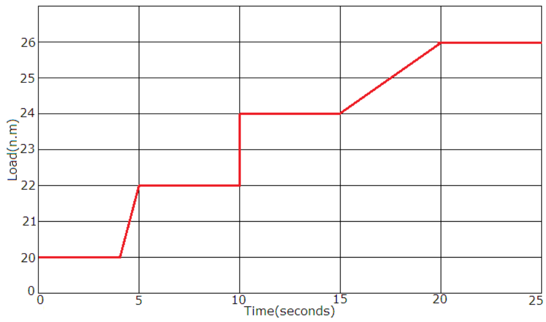

Figure 8. The load torque of DC motor 1

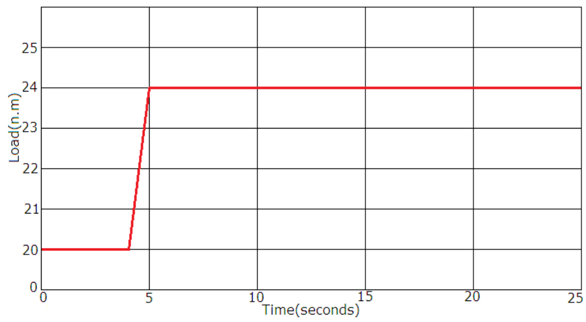

Figure 9. Load torque of DC motor 2

From Figures 8 and 9 it may be noticed that the load is changing. The motors have the same load 20 Nm for the first 5 sec and after that the load of motor 1 jumps to 22 Nm and the load of motor 2 jumps to 24 Nm, so the selector switch choose the torque of motor 2 as reference (the higher torque), the load torque of motor 2 maintains to be the reference until it reaches 15 sec at which the load torque of motor 1 becomes greater than the load torque of motor 2, so the switch will select load torque of motor 1. Figure 10 shows the load torque of the motors in one plot for easy comparison.

Figure 11 represents the output signal of the switch which is also the reference torque that was used to select the speed input of both systems. The proposed study is implemented using MATLAB/Simulink software. The result of the simulation is depicted in Figure 12. In this figure the speed of the first motor is plotted in red dots and the speed of the other motor is plotted in dashes. From this figure it can be noted that the two motors are synchronized with each other and the drop in the speed at time 5 sec and 15 sec represents the change in torque value which is used to calculate the speed reference value. The increase in load in one motor more than the other creates that drop in speed, as the power is constant (since the power equals the radian per second speed multiplied by the torque value) the increase in one of them causes a decrease in the other.

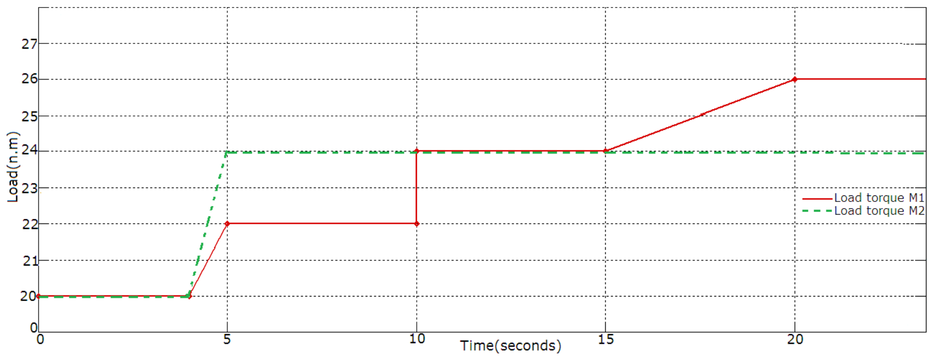

Figure 10. Load torque of both motors

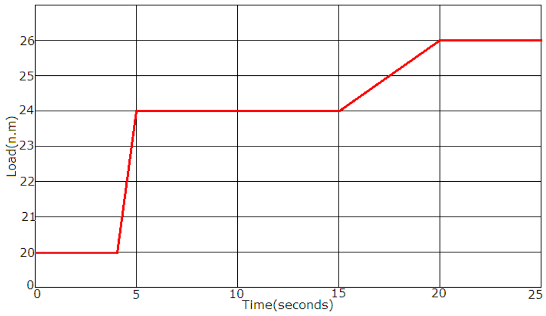

Figure 11. The switch output

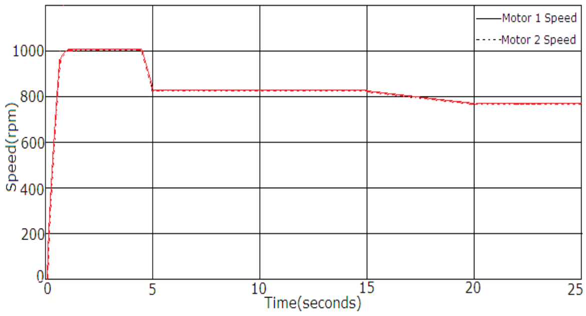

Figure 12. The speed of both motors

In real life the speed synchronizing between two DC motors can't be achieved in ideal way, so there are some deviations between speeds. This very small deviation is shown in Figure 13. As shown in this figure, after zooming in, there is a speed deviation between the two-motor speeds, where the first motor speed is higher than the second motor speed by 0.22 rpm.

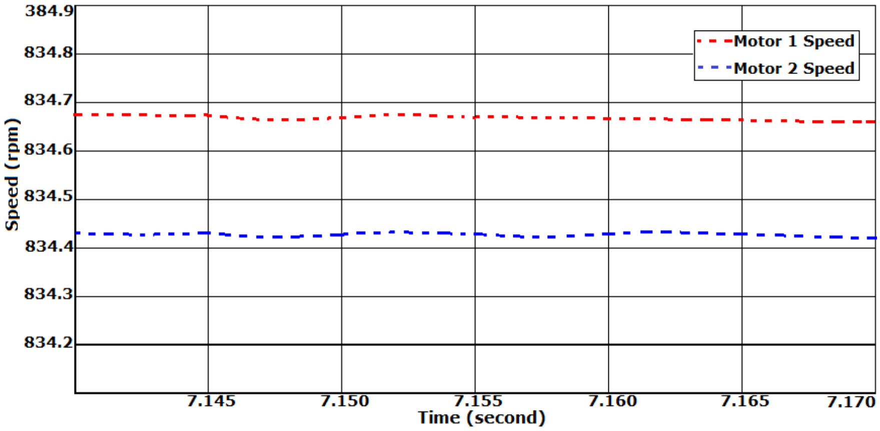

Figure 13. The speed deviation of two synchronizing motor

In such systems, sharp weakening of the shunt field is an unlikely event. The partial or complete loss of the shunt field results in a sharp reduction of the generated back electromotive force. This causes a big increase in armature current, without a corresponding rise in torque. Therefore, speed synchronizing between two DC motors requires a specific protection and some general protection. The main protection of the motor protects it from overcurrent, overvoltage and under voltage, but in matter of synchronizing DC motor there should be communication between the protection devices of the first motor and the second one. Therefore, coordination is required between the protection devices of both motors, so that if any of them trips the other should trip immediately.

5. CONCLUSION

In this work, a dual-motor speed synchronizing system was built, based on armature control for two same DC motors. Starting by building single-motor speed control system based on armature control using the PID controller. Then tuning the PID controller parameters was used to find the best parameters of the controller, and after that the performance of this system was analyzed to see if it is suitable to be the base of the studied two-motor system. The performance characteristics were excellent, so it was used for building the system of two armature control, where the synchronization between the two motors is achieved by their torque value with respect to each other. Selection method was used to set the motor with higher torque and use this torque to calculate the reference speed for both motors. Other method that can be used for synchronizing is the armature current, which is proportional to the induced torque. From the results, it is easy to notice that the required synchronization has been achieved with very high accuracy, as the deviation in speed is less than 0.25 rpm (which is about 0.00025%). Therefore, the used technique shows high accuracy and transient performance of the system.

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