Mendocino motor and a different approaches to its control

Conference Paper · January 2012

2 authors:

Zdeněk Novák
Czech Technical University in Prague

Milan Hofreiter
Czech Technical University in Prague

Mendocino Motor and a Different Approaches to its Control

Zdeněk Novák, Milan Hofreiter
Dept. of Instrumentation and Control Engineering, Faculty of Mechanical Engineering, Czech Technical University in Prague, Technická 4, Prague (16607), Czech rep., *Z.Novak@fs.cvut.cz*, *Milan.Hofreiter@fs.cvut.cz*

***Abstract*—Design and principle of Mendocino motor. Speed of Mendocino motor is controlled via intensity of incident light. The halogen lights voltage is changed using PWM. A device called “Control unit” is designed to set the PWM, measure speed of Mendocino motor and communicate with computer. Software Matlab Simulink is used to create different approaches to control Mendocino motor, with using Matlab S-function as a bridge between Simulink and Control unit.**

Keywords-Mendocino motor; Control unit; PWM; Matlab Simulink; control; S-function

I. INTRODUCTION

The first idea of motor powered by solar energy - causing electromagnetic induction in its coils within magnetic field (and therefore its rotation) - came probably from the Bell telephone laboratories in 1962 [1]. Its description was made by Daryl Chapin. It was probably only an experimental device for presenting the sun as a source of power, because scientists just developed the modern photovoltaic cell (1953). Motor was referred as a “Light commutated motor”. At this time motor didn't levitated on a magnetic cushion. This was made later by Larry Spring in 1994, and because his experimental laboratory was located in Mendocino Coast, motor was named “Larry Spring's Magnetic Levitation Mendocino Brushless Solar Motor”, or simply “Mendocino motor “[2].

This paper is based on the Master’s thesis [3]. During this thesis, a control unit was designed as a Printed Circuit Board (PCB) assembled with C8051F340 microcontroller with a possibility of connection to PC via Serial port. Because of a low efficiency of the solar panels, two halogen lamps were used as a source of light for powering these solar panels, instead of using solar energy. By creating current in their circuits, magnetic field was created; thus rotation of the Mendocino motor. Lamps voltage, and therefore light intensity, was set by control unit using Pulse Width Modulation (PWM). For measuring the Mendocino motor speed, sensor based on the principle of photocell was used. Because the Mendocino motor is not a commonly manufactured product, it was designed and built in the university laboratory. Matlab Simulink software was programmed to communicate with Control unit and - based on the control process - set lamps voltage. Because there are several options how to design control process, whole installation is located in the Laboratory of Control Engineering as a study material for students of a Control engineering courses, e.g. to show controllers tuning, identification of systems, etc. Other usage of the Mendocino Motor would require more investigations.

II. DESIGN AND CONSTRUCTION OF THE MAIN PARTS

A. Mendocino Motor

So far, there are 2 basic design types of the Mendocino motor. The first one is based on the use of square profile of the motor with 2 coils, each one connecting opposed solar panel into series and wired around opposed corners of motor. A very good work about this design is [4]. The second type of Mendocino motor design is based on polygonal profile – its body has a shape of pentagon or hexagon [5]. In this kind of Mendocino motor, every coil is connected to one solar panel and these coils are located inside of Mendocino motor. Designed structure of model is in Fig. 1.

The principle of the motor is as follows. Every coil is connected to the opposite solar panel (see Fig. 2). Turning one of lamps on creates voltage at desired solar panel. Current will start to flow through circuit, causing magnetic induction inside and outside of coil. Directions of magnetic field lines depend on a direction of current in circuit and inside of coil these lines are parallel. Permanent neodymium magnet is located under motor. If the lines of magnetic induction have same direction as lines of magnet, attractive force will appear, making motor to rotate under clockwise (lamp 2 turned on). If the same lines have opposite direction, then repulsive force will come in action and try to switch sides of coil to the right direction (S pole of coil to N pole of magnet), making motor to rotate clockwise (lamp 1 turned on). That allows us to spin Mendocino motor, create our wanted direction of rotation or simply deceleration of motor to required speed.

The levitation principle of the motor is in Fig. 3. Motor is levitating above 4 neodymium magnets, which are replacing the bearings for no friction. Because of opposite poles of neodymium magnets, motor is pushed towards the wall, making it stable. Correct distance of bottom magnets is critical for stability of the motor. Function of the central neodymium magnet was already described in Fig. 2.

Motor schematics were drawn with regard to production and technological capabilities. It was decided to use laser cutting for motor’s parts because of their complexity, and as a material aluminum because of its light weight. Type of solar panel is referred as Monocrystalline silicon solar panel 0.5V/250mAh. This panel was chosen because of its good dimensions (65 x 20 mm) for hexagonal shape Mendocino motor design. Accordingly to [6], Si solar panel maximum efficiency should be between 10-20%.

After testing of solar panels - as a source of light - 28W and 20W halogen lamps (with 12V nominal voltage) were chosen. Coils were designed to be able to create as strongest magnetic field as possible, which should lead to interaction of this magnetic field with bottom magnetic field of permanent magnet; forcing motor to spin. Magnetic induction B [H] in case of coil with solenoid shape can be described as [7]:

$$B = \mu_0 \cdot \frac{N \cdot I}{l_{selenoid}} \tag{1}$$

where µ0[H/m] is a magnetic constant, N is a number of turns of one coil, I[A] is a current in the circuit of one solar panel and coil, and $l_{selenoid}$ is a length of coil with solenoid shape. The magnetic moment for coil with N turns is [7]:

$$\vec{M} = N \cdot I \cdot S \, x \, \vec{B} \tag{2}$$

where M[A.m2] is a magnetic moment and S[m2] is a cross-section of the wire of coil. As we can see, magnetic induction, as well as a magnetic moment, is increasing with higher number of turns of the coil and the passing current. However, with increasing number of turns of the coil, coil's length is also increasing - therefore its resistance - and therefore, according to Ohm's law, current will be reduced.

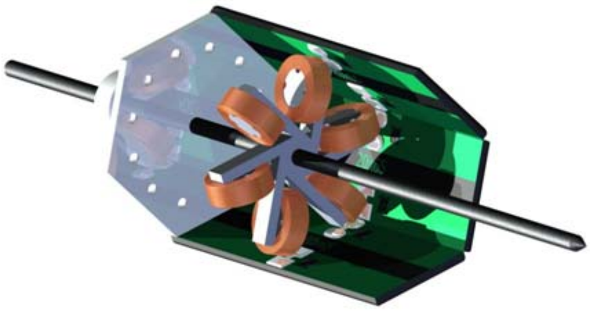

Figure 1. Inner structure of Mendocino motor with hexagonal body shape

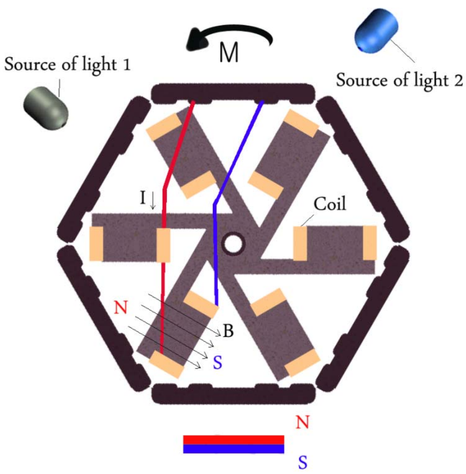

Figure 2. Principle of the Mendocino motor with inner coil

Since the production of coils was planned to carry out by hand in the laboratory, its shape can't be perfect. It is a multilayer type of coil; its inductance is a question of its geometry and can be described using Wheeler's formula for short cross-wound coil [8]:

$$L = \frac{0.315 \cdot r^2 \cdot N^2}{6r + 9a + 10b} \tag{3}$$

where L[µH] is a coil's inductance and dimensions r, a and b [cm] are dimensions of coil accordingly to Fig. 4 (left).

Thus, final dimensions for coil were chosen based on the limits of the real motor proportions (for example, hexagonal profile has its dimensions given by width of solar panel and space inside is limited by these dimensions) and optimizing parameters mentioned above. After choosing length, number of turns of the coil and diameter of the coil, Mendocino motor was built (Fig. 3 bottom) and equipped with sensor for measuring its speed (rays of alternating opaque and transparent parts) in its left part in front of the wall. Detail of the position of lamps is in Fig. 5 (bottom).

The real winding of the coil is made of copper and is shown in Fig. 4 (right). Coil's core is made of aluminum (as same as the motor's structure) and even it has a slightly different magnetic constant μ_0 from the air - during the coil's design - the magnetic constant for the air was used. A very good description of choosing right proportions for coil in case of square motor design is written in already mentioned [4].

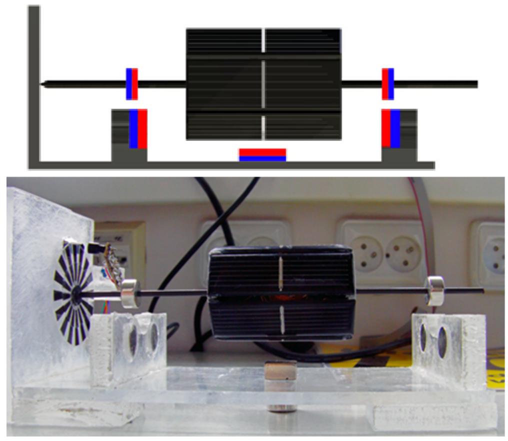

Figure 3. Top - Principle of levitation. Bottom – Real Mendocino motor

Figure 4. Left – dimension of short cross-wound coil. Right – real winding of coil

B. *Control Unit*

A Control unit was created to control Mendocino motor using computer. Its main part is PCB assembled with C8051F340 microcontroller produced by Silicon Laboratories. Microcontroller was programmed for these main functions:

- Half-duplex communication with computer
- Handling operation of LCD, where user can choose between information about actual speed (in RPS) or actual power in lamps (in percents from 0%-100%)
- Setting lamps voltage using PWM
- Calculating actual speed based on tachometer settings

PCB is connected with PWM circuit board, which is assembled with two MOSFETs, used to control lamps voltage. Everything is packed in a plastic kit with a front LCD display, terminal at right side for connecting outer devices, such as lamps and tachometer; and a serial port at back side for connection with computer. While using PWM, transistors temperature is rapidly increasing and therefore kit is also equipped with a fun allowing maintaining functionality of the control process.

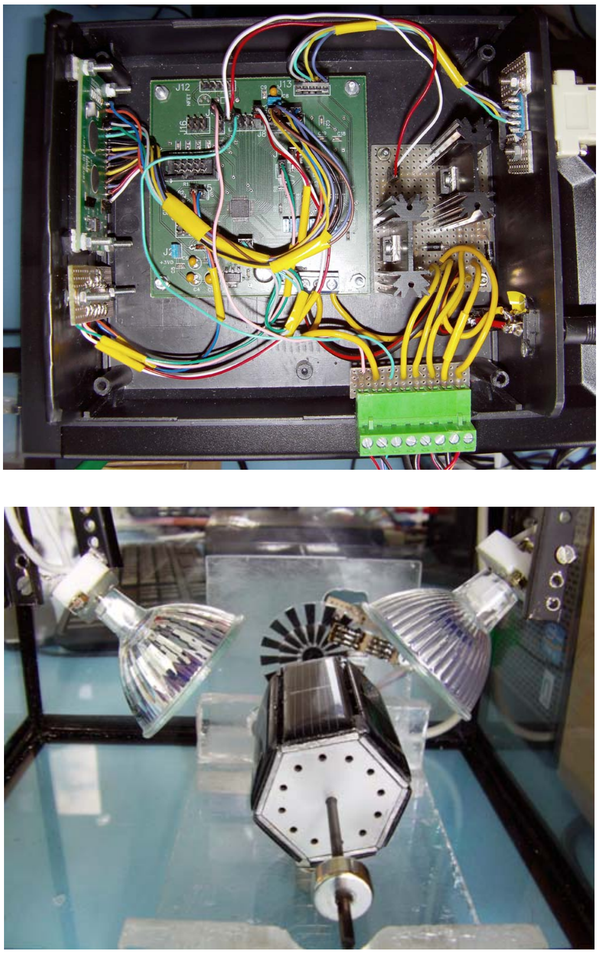

Figure 5. Top – inside of Control Unit. Bottom –position of lamps above Mendocino motor

Tachometer was created on principle of photocell. Its main part is already shown in Fig. 3. Microcontroller is counting a number of interrupts during a short period (250 ms) and calculating speed of motor using that number. Accuracy of that operation is given by number of used rays on a disk (alternating opaque and transparent) and can be further refined by further math operations, e.g. mean of the last 3 measuring.

III. CONTROLLING MENDOCINO MOTOR

To control Mendocino motor, Matlab Simulink was used. The block diagram was designed based on the used control process. Basically, it consists of 2 main parts where the first one is a part of the controller. It was decided to use 3 ways of control:

- PID (proportional–integral–derivative) controller with using only one lamp for acceleration of the motor
- PID controller with using both lamps, one for acceleration of the motor and second one for its deceleration (further on, this block will be referred to as a Break block)
- 2-state controller

Second part of the block diagram is the S-function block. S-function is a user definable function and it can be written in C, Matlab or FORTRAN, but it has to meet requirements of S-function standards. It is using a system of flags and their order is also given by S-function standards, including the order of their calling which is fully controlled by Matlab Simulink. For further understanding of S-functions is recommended [9] or built-in Matlab help. In Mendocino motor control, this function is used for opening communication port with the Control unit, sending actual settings of PWM to the Control unit and receiving actual speed of Mendocino motor from the Control unit. Therefore S-function block input is a control variable from the controller block and its output is actual speed of the Mendocino motor.

A. *Controlling Mendocino using PID controller with and without a Break block*

A block diagram for controlling Mendocino motor with using a Break block is shown in Fig. 6, also with the inner structure of the controller and inner structure of a Break block.

Control variable has its maximum and minimum given by range of an 8-bit number - which is send to Control unit as a setting for PWM - therefore, PID controller is equipped with Anti-windup to prevent exceeding this range. Derivative part of PID controller is equipped with filter (filter order N).

Even the motor is capable of rotation on both sides, for the laboratory purposes and testing was decided to use only one way of rotation. For that reason, a Break block is using only 2 output values where the first one turns the lamp off and second one turns the lamp on with nominal voltage (12V). This Break block contains Switch block which compares speed difference (e) with given criterion (see Fig. 6). If the speed difference (e) is higher or equal to value of the threshold criteria, block will pass through the top input (lamp on); otherwise it will pass through the bottom input (lamp off). If a desired speed is lower

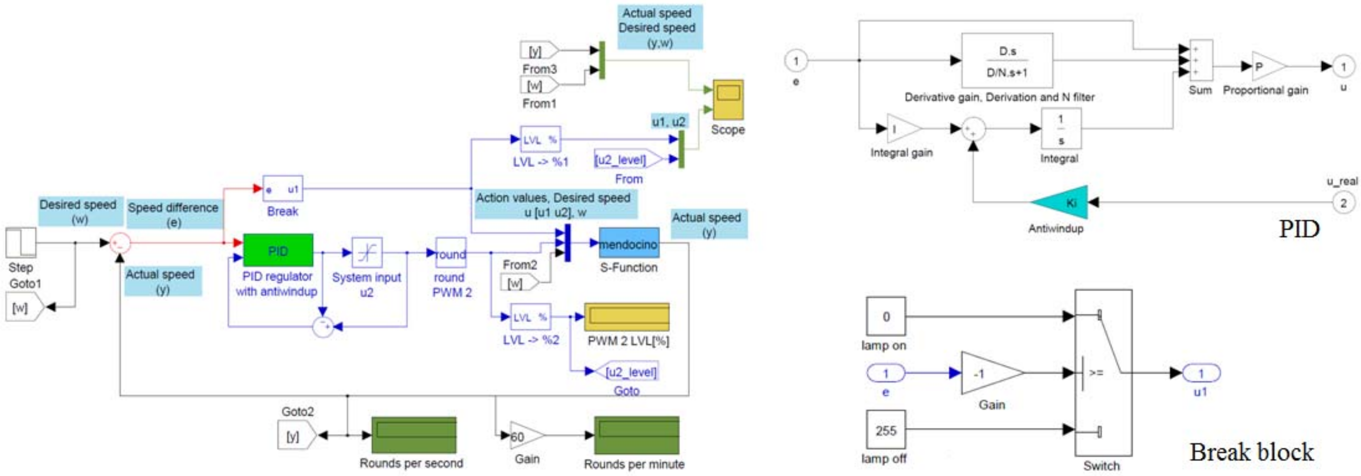

Figure 6. Left– Block diagram for controlling Mendocino motor (action value is equal to control variable). S-function has also “w” value as input for generating record from the control process into the text file. Round block is used to keep control variable as a integer number, which can be send to the Control unit as a 8-bit number. Top right –inner structure of used PID controller. Bottom right – inner structure of Break block

than actual speed, speed difference is always higher than 0, so block Gain (-1) has to be used for inversion. For example, threshold is set to be 0.25 and desired speed is 5. Until actual speed is smaller than 5.25, Break block will keep forwarding value for setting lamp off. When the actual speed will be equal or higher then 5.25, lamp for deceleration of motor will be turned on with nominal voltage 12V.

Control scheme is the very same for the case of using only PID controller, except that a Break block is missing and second lamp therefore remains off.

B. Controlling Mendocino using 2-state controller

This diagram differs from the previous one only in the part, where PID controller with Anti-windup is switched with another Brake block. This control algorithm works with both lamps where one of the lamp’s voltage is always set on nominal voltage, based on if motor should accelerate or decelerate.

IV. Results of the Application of Control Algorithms

A. Using PID controller without a Break block

Three different settings for PID were tested. In all diagrams, control variable (u1, u2) was changed to percent scale, where 100% means maximum value of action value and therefore lamp’s voltage is at nominal value (12V). Desired speed was set to 15 RPS (rates per second) in the first 150 seconds and then changed directly to 11 RPS by Step block in Simulink. Because sensor for measuring motor’s speed is very sensitive, start of the speed measurement is delayed for 5 seconds at the beginning of process and output is set to 0. Therefore all diagrams contain a speed jump after first 5 seconds.

When the motor reaches speed around 3.5 to 4 RPS, it has to overcome its own resonance. This effect can be caused by imperfection of motor balance and also position of permanent magnet. This effect was partially suppressed in other measurements by small change of permanent magnet location and position of lamp, so the motor surpass this area faster and its effect of vibrations disappears. Own resonance effect and the first setting of PID controller is in Fig. 7.

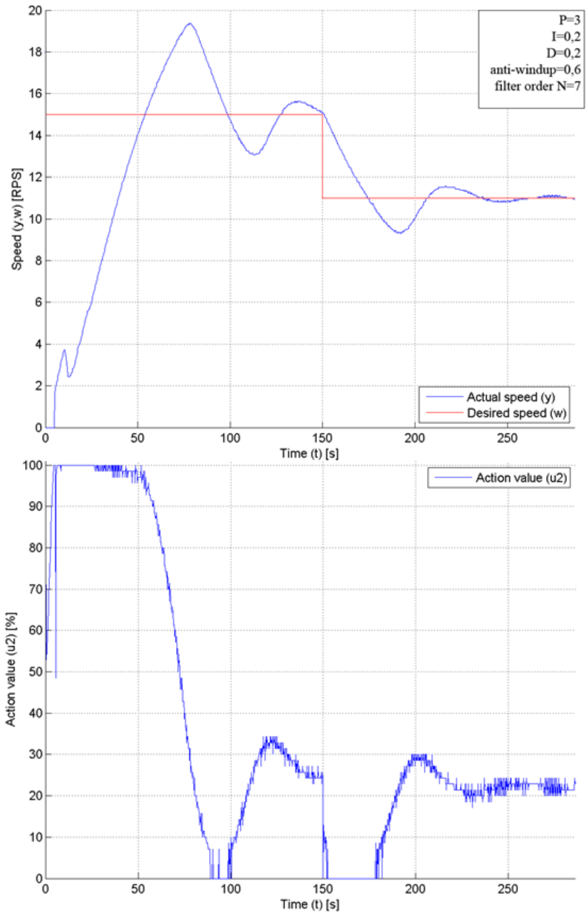

Figure 7. First setting for PID controller without using a Break block and own resonance effect around 3 RPS (around 15 seconds)

It is visible, that these settings are not very ideal because of overshooting desired speed value. Therefore 2 more settings were used to improve this situation and results of a better one are in Fig. 8.

However, with using only one lamp for acceleration of the motor, we cannot force motor to slow down. In this case, motor slows down only due to the air friction and friction between its tip and wall surface (see Fig. 4). This process is visible between 150-175 seconds of control process in Fig. 8, where the lamp is turned off and motor decelerates to desired speed 11 RSP.

B. Using PID controller with a Break block

Settings for PID were changed. It is important to set right value of threshold for Switch block (in the Break block), allowing control process to slow down motor after exceeding desired speed. A control process is in Fig. 9.

Comparison of both processes is in Fig. 10. In the case of changing speed from 15 RPS to 11 RPS with using only one lamp, it takes approximately 25 seconds. With using Break block's lamp it takes approximately 12 seconds, which is a noticeable difference. Same noticeable difference is in total time of regulation process (first point, where the actual speed and desired speed are almost same with only a small change in time), as well as in overshooting desired speed.

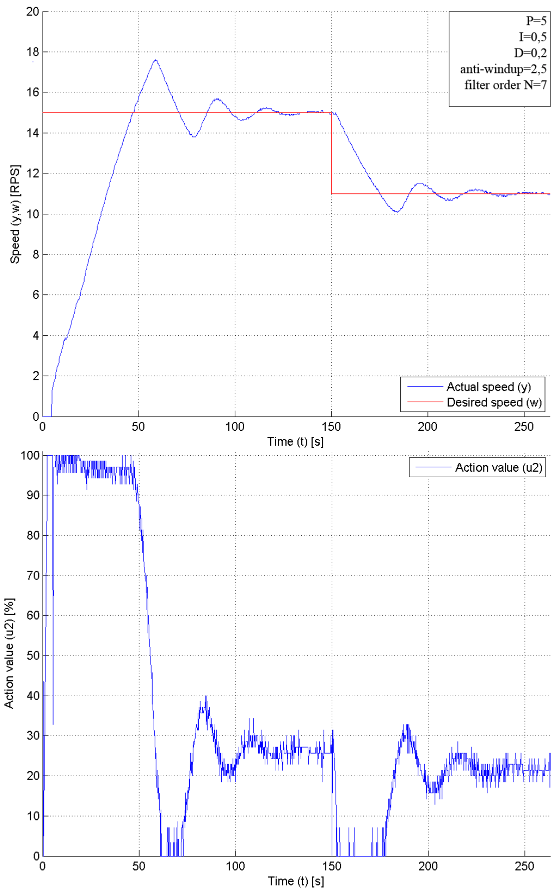

Figure 8. Last setting for PID controller without using a Break block

C. Using 2-state controller

Two-state controller was used as an alternative for controlling Mendocino motor. Because it consists of 2 Break blocks, it has only 2 settable threshold parameters (one for each). These parameters affect how much the motor actual speed will be oscillating around desired speed. A result of the control process is in Fig. 11.

V. CONCLUSIONS

This paper presented basics of how to design and control Mendocino motor. The Mendocino motor will be further used in the Laboratory of Control engineering for study purposes.

Optimal operational speed of designed motor is from about 10 RPS (600 RPM) to 20 RPS (1200 RPM) in the case of using 20W halogen lamp. Maximum speed of motor is around 25 RPS (1500 RPM) (see Fig. 12). To reach a higher speed, lamp with higher electric power is required. Rates around 3-5 RPS are not recommended due to the imbalances and effect known as the resonance disaster.

In the future, control algorithm can be improved. Because there is a direct connection between used lamps voltage – therefore emitted light – and speed of motor, it is possible to create algorithm, which will use this mapped area of dependence and PID controller will be used only for rates close to desired speed. Using these improvements would lead to energy savings and therefore to higher efficiency.

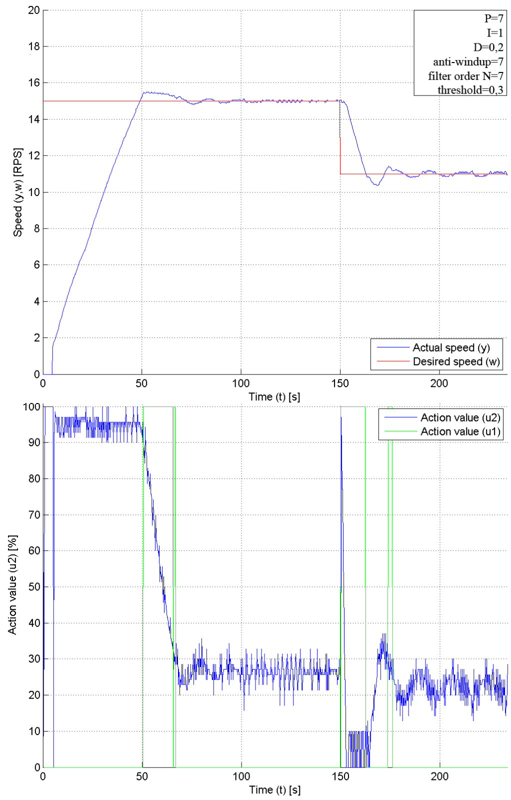

Figure 9. Using PID controller and a Break block

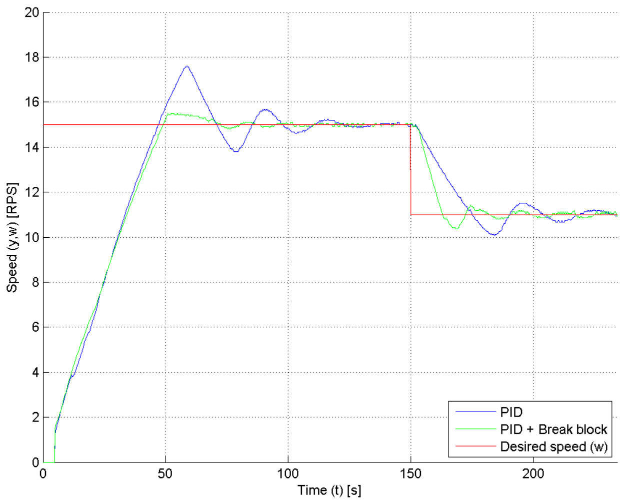

Figure 10. Comparison of the control process using PID controller with and without a Break block

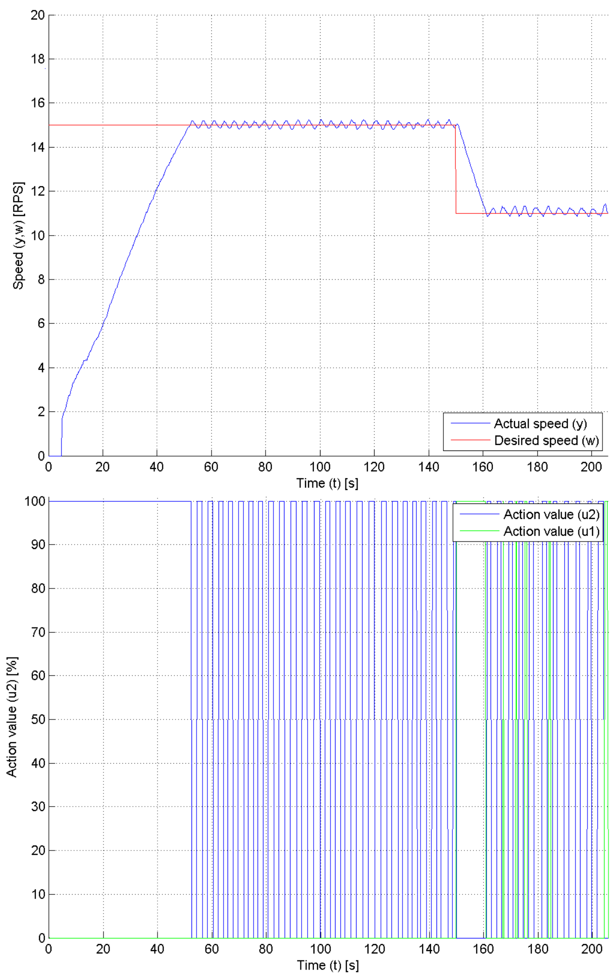

Figure 11. Using 2-state controller

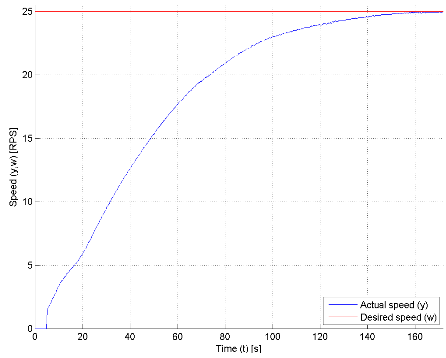

Figure 12. Maximum speed of the Mendocino motor (20W halogen lamp)

ACKNOWLEDGMENT

The Author would like to thank to his supervisor (coauthor) for the support and permission to use laboratory of automatic control for experiments. Also another grateful acknowledgement belongs to Martin Novák for his consultations and advices about electronics, Šárka Němcová for the theory of light, Pavel Trnka for his help with equipment in laboratory and his advices, Daniel Tischler for his consultations about magnetic fields; and to other colleagues from the Dept. of Instrumentation and Control Engineering and other departments, Faculty of Mechanical Engineering, CTU in Prague for their specialists advice and technical assistance. Last acknowledgement is for Jan Brajer from RCMT, CTU in Prague, for his laser cutting consultation and creating parts of Mendocino motor in the future.

REFERENCES

[1] Daryl M. Chapin., Bell Telephone Laboratories, “Energy from the sun,” 4th edition. Baltimore: Waverly Press, 1964.

[2] Larryspring.com, “Larryspring School of common sense physics”, [online]. [ref. date 2012-03-17]. Available at: http://www.larryspring.com/sub06_motors.html.

[3] Z. Novák, “Controlling speed of motor powered by solar energy, Prague, 2012. Master's thesis. Czech Technical University in Prague. Supervisor prof. Ing. Milan Hofreiter, CSc.

[4] W. Amrhein, H. Mitterhofer, E. Marth, G. Bramerdorfer, “Aufbau eines Mendocino-Motors,“ [online], Linz, 2010 [ref. date 2012-05-18]. DVR 0093696. University research project, Johannes Kepler University Linz, Available at:http://www.bis0uhr.de/projekte/magnet/projektseminar.pdf.

[5] MANFRED KLOSE (GbR), “Mendocino Motor” [online]. 2010 [ref. date 2012-05-20]. Web page dedicated to Mendocino motor design. Available at: http://www.mendocinomotor.de

[6] Martin A. Green, K. Emery, Y. Hishikawa, W. Warta, Ewan D. Dunlop. “Solar cell efficiency tables”, Progress in photovoltaics: Research and Applications. 2012, vol. 20(1), pp 12-20. ISSN 10627995. DOI: 10.1002/pip.2163. Available at:http://doi.wiley.com/10.1002/pip.2163

[7] B. Sopko, L. Samek, F. Černý. “Fyzika 2”, Praha: Vydavatelství ČVUT, 2005. ISBN 80-01-03194-2

[8] Langford-Smith Fritz., Amalgamated Wireless Valve Company, “Radiotron Designer's Handbook“, Reproduced and Distributed by Radio Corporation of America (1960). Originally printed in Glebe (Australia): Wireless Press, 1952, fourth edition

[9] MathWorks: Matlab and Simulink for Technical Computing. Maintaining Level-1 MATLAB S-Functions: Writing S-Functions in MATLAB [online]. 2012 [ref.date 2012-05-24]. Available at: http://www.mathworks.com/help/toolbox/simulink/sfg/f7-67615.htm