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STUDY REGARDING THE SOLAR TRACKERS USED FOR PHOTOVOLTAIC MODULES

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Abstract: *This study proposes a study on the sun tracking mechanisms used for increasing the energetic efficiency of the photovoltaic panels, through the automatic optimal positioning of the PV panel in accordance with the sun path. The study is segmented in two parts, as follows: for beginning, a general systematization of the mechatronic solar trackers is performed from the point of view of the two main components - the mechanical device, and the control device; then, a case study is developed for a dual-axis azimuthal tracking mechanism with the aim to establish the optimal combination between the control scheme and the type of controller.*

Key words: *sun tracking, PV panel, mechatronic system, efficiency.*

1. Introduction

The continuous depletion of the fossil fuels resources caused the energy market to direct towards the industry of renewable resources systems, in which electricity and heat can be produced through methods that are environmentally friendly and free from pollution, in short, obtaining green energy. It is more and more common to use sun, water, wind, geothermal energy and biomass to generate energy.

Solar energy is the most important source of renewable energy and it offers a huge potential of generating green energy, without emissions of pollutant gases in the atmosphere. The systems that use solar energy in order to generate electric power are applied for various purposes, like pocket calculators, toys, automobiles, satellites and others. The dimensions of the photovoltaic systems that are used for electricity supply, range from one module systems up to an array of modules of great dimensions and power [9], [12], [15].

When the solar radiation hits the photovoltaic module, then the photovoltaic effect takes place at the level of the solar cell and in this way, electricity is produced. One module is composed of several photovoltaic cells connected in series or/and in parallel in order to produce sufficient intensity for the usage. The generation of electricity depends on the module conversion efficiency, on climatic factors, on the temperature at the cell level.

A solution for improving the efficiency of photovoltaic systems is the use of tracking mechanisms, which change the positioning of the system in order to maximize the quantity of captured solar radiation [3], [5], [6].

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2. The Systematization of the Solar Trackers

According to the two motion axes of the Earth, tracking systems can be bi-axial and mono-axial [8], [13], [14]. The bi-axial tracking systems ensure a precise positioning by performing the two movements, daily (earth rotating around it own axis) and seasonal (earth revolving around the sun). The mono-axial tracking systems only perform the daily movement, while the seasonal movement is fixed at a pre-defined optimal location specific angle, called elevation angle. The mono-axial tracking systems have the advantage of lower costs due to fewer elements and functioning with a single motor (actuating) source, but they have the disadvantage of lower energy efficiency compared to the dual-axial tracking mechanisms.

The bi-axial tracking systems can be classified in 4 categories, according to the position of the axes of motion (Figure 1): equatorial (a), pseudo-equatorial (b), azimuthal (c) and pseudo-azimuthal (d) [4]. Figure 1 displays a graphical representation of the bi-axial tracking systems, in a vertical plane with the East-West axis as normal, were "1" represents the diurnal movement and "2" the seasonal movement (elevation/altitude).

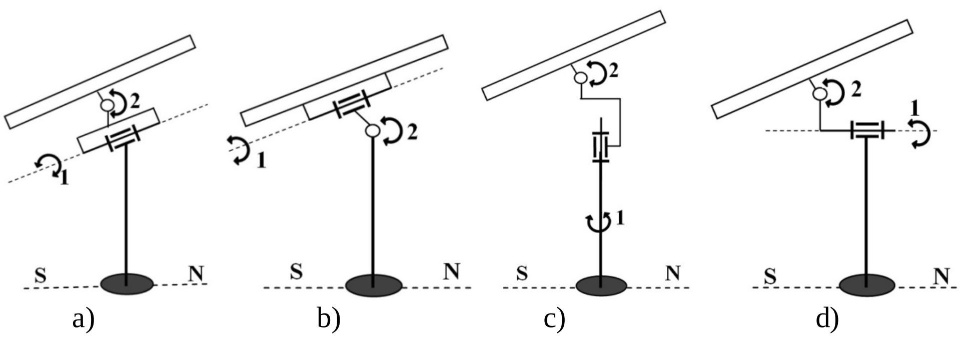

Fig. 1. *Dual-axis solar trackers* [4]

The equatorial tracking systems have the diurnal movement axis as fixed axis, which is parallel with the polar axis. The elevation motion axis varies according to the diurnal axis. The advantage of the equatorial systems is that the orientation/positioning according to the elevation axis is made only seasonally (this is also where the name of seasonal movement comes from), but in terms of construction, this solution is more difficult to complete and it is less stable (it needs balancing elements).

The fixed axis of the pseudo-equatorial tracking systems is the elevation motion axis, which is displayed horizontally, parallel to the East-West axis. In terms of construction, this solution is more simple and more stable (it does not require a rigorous balancing), but it requires frequent tracking which follows the elevation axis (in particular during the warm seasons).

The azimuthal tracking systems have as fixed axis the diurnal movement axis (azimuthal), which is displayed vertically (perpendicular to the observer's plane). The altitude motion axis (elevation) varies according to the diurnal axis, which requires the correlation of the two movements throughout a day (because of their interdependency), which makes the control of the system more complicated. The azimuthal tracking systems have the advantage of a more stable structure and they are used frequently for the orientation of the photovoltaic platforms.

As in the case of azimuthal systems, the pseudo-azimuthal systems have as fixed axis the diurnal movement axis, which in this case is displayed horizontally, and is parallel to the North-South axis; the variable axis is the altitude motion axis (elevation). These systems need a daily correlation of their movements as well, but they also have the advantage of a stable structure. The pseudo-azimuthal systems are used frequently for the orientation of platforms of photovoltaic modules arranged in rows.

With respect to the functioning principle, two fundamental types of tracking systems can be identified: passive and active. The functioning of the passive tracking systems is usually based on the thermal expansion of a Freon based liquid, from one end of the system to the other, due to the heat sensitivity of the working fluid.

The active tracking systems are mechatronic systems based on positioning devices which are usually electrically driven, and include motors (rotary or linear actuators), rotation decelerators, mechanisms, clutches etc. In general, the new systems are based on mechanisms with articulated bars, mechanisms with gears, chain or belt transmission. The orientation of photovoltaic modules through active systems can help improve the efficiency of the conversion system by values ranging between 20 % and 50 % compared to the fixed panel [18], [19], [21].

With respect to the active tracking systems control, the literature presents several closed-loop systems, based on the use of photo-sensors, which are responsible to detect the sun position and send electric feedback to the motor controllers [10], [11]. However, the photo-sensors based tracking can include errors in detecting the real position of the sun on the celestial sphere in variable weather conditions (e.g. cloudy sky) and requires automatic drivers to position the system towards the east at the beginning of the day.

The alternative is the open-loop systems, based on algorithms/programs which provide motor control pre-defined parameters, according to the position of the sun on the celestial sphere (the astronomical movements of the sun-earth system) [1], [2]. These positions can be determined precisely due to the fact that they depend on the solar angles, which can be calculated for any geographical area [17]. By using this control technique, based on pre-defined movement parameters, the errors generated by the use of photo-sensors can be corrected (systems are not affected by clouds, variations of radiations or other optical circumstances). In the case of computerized astronomical systems a reference positioning is required, which can be adjusted at the beginning of operation, but which requires recalibration.

Another solution are the hybrid systems, which incorporate a certain type of position sensor in order to automatically search for and calibrate the astronomical control system. In addition, the tracking system can be adjusted in order to provide the maximum of energy, to position itself in the beginning or to correct itself during the functioning cycle.

With regard to the control element - the controller, the published literature presents different solutions, ranging from the basic controllers in the PID family (Proportional-Integrative-Derivative) to the robust or adaptive modern controllers (Fuzzy Logic Controller - FLC) [16].

Another solution are the intelligent tracking control systems, that are capable to adapt to the weather conditions, by taking tracking decisions in accordance to the data sets recorded in real life environment - solar radiation, temperature, wind etc. The functioning of intelligent control systems is defined by the next sequence: meteorological data monitoring, extracting phenomena (past rules), inference of rules, proposing trajectories and acting upon the proposed trajectory.

The control system can be designed to consider a series of monitored parameters, such that the control strategies used for the photovoltaic tracking systems can be classified as follows (Figure 2): single-loop control systems (a) - they usually monitor the angle position of the PV system, two-loop control systems (b) - they monitor position and velocity, three-loop control systems (c) - they monitor position, velocity and current. In Figure 2, M is the motor force, C - the controller, MO - the orientation (tracking) mechanism, and T - the imposed trajectory (the reference signal).

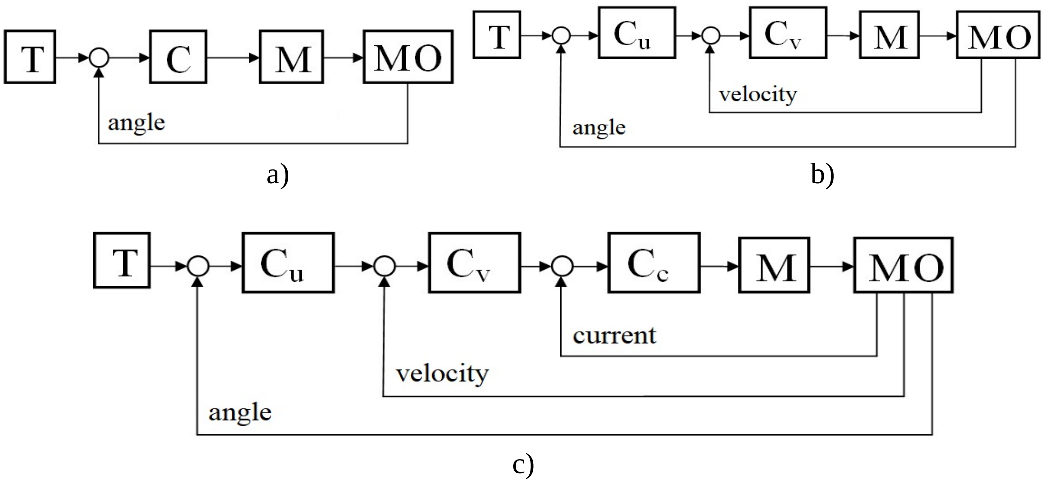

Fig. 2. *Single-loop (a), two-loop (b) and three-loop (c) control schemes*

The systems shown in Figures 2b, c, which measure two, respectively three parametres, are called cascade control systems. This type of control uses the set point of the external controller in order to control the reference value of the internal controller. Although this control strategy is more complex than the single loop control, it ensures important benefits, such as the ability to approach a number of perturbations that influence the process and the improvement of system performance. There are certain requirements of the cascade control system, which include: the dynamics of internal control loop performance has to be faster than the dynamics of the external control loop; the internal control loop has to be measurable and controllable; the internal loop has to influence the external loop.

3. Case Study

The study carried out in this article concerns the determining of the optimal control strategy in an open circuit for an azimuthal type of tracking system, whose virtual prototype designed with the help of CAD (CATIA) and MBS (ADAMS) software solutions is displayed in Figure 3. The virtual prototyping tools provide important benefits, as pointed out in [7], [20]. The objective of the study is to identify the optimal combination (in terms of complexity, cost and performance) between the single/multi-loop control scheme (in terms of number of monitored parametres) and the type of controller. The study assumes to start from the use of a very simple type of controller (filter type) and to identify the minimum number of control loops necessary in order to ensure an appropriate behaviour of the system (in terms of stability, robustness).

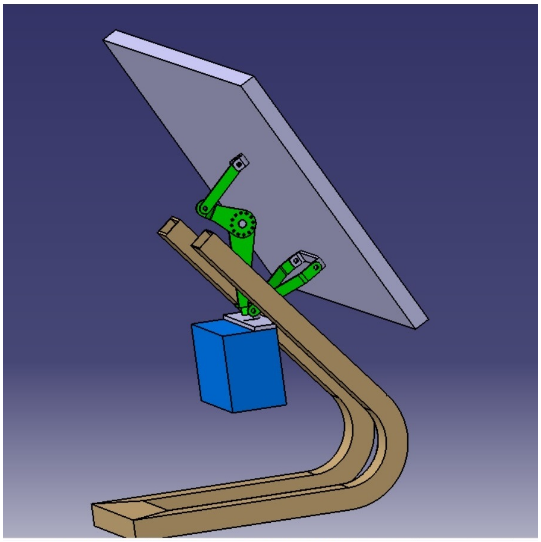

Fig. 3. *The virtual prototype of the dual-axis sun tracking mechanism*

The main (daily) movement of the photovoltaic panel is done with the help of a worm gear servomotor, which moves the panel on the East-West direction by rotating the whole system relative to the fixed pillar around the vertical axis. The altitudinal (elevation) motion is driven by a rotary actuator, the motion being transferred to the photovoltaic panel (which rotates around the horizontal axis) by a rod-crank mechanism.

The comparative analysis is made based on the following considerations: simulation is made for a representative day of the year, namely the summer solstice; the orientation of the PV panel is achieved through a continuous motion, the diurnal angle of the panel is the same as the angle of the sunray ($\beta^* = \beta$), for the day in question the variation diagram is the one in Figure 4, while the elevation angle is $\gamma^* = 42°$ - optimal position for the day in question, in Braşov area [*]; the duration of the simulation corresponds to the time interval sunrise - sunset: [4:21; 19:81]; no external forces act upon the system.

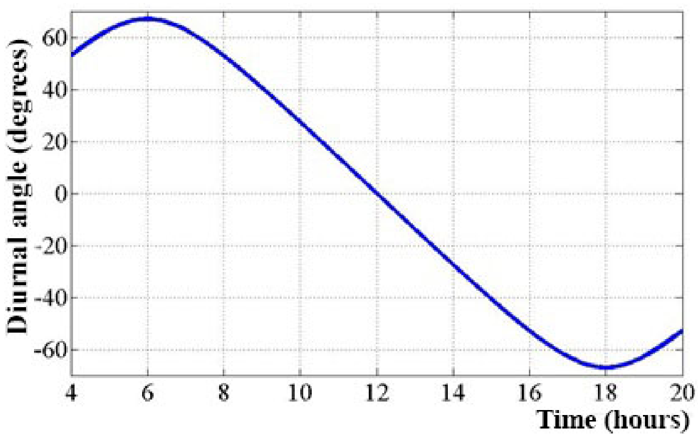

Fig. 4. *The variation of the diurnal angle*

According to what was previously mentioned, the most simple control scheme corresponds to the single monitored parametre option (diurnal angle), while a low-pass filter is used (LPF) as a control element (controller). This filter is created by putting a resistor and a capacitor in series which allows the low frequency signals to pass, which means that it attenuates signals with frequencies higher than the cut-off frequency. Using the Laplace transform, the LPF controller transfer function is given by the equation:

$$\frac{Y(s)}{X(s)} = \frac{K}{\tau s + 1}, \tag{1}$$

where X(s) is the input signal, Y(s) - output signal, τ - response time constant, K - amplification factor of the controller.

The time constant represents the time interval in which the response of the system reaches 1-1/e ≈ 63.2 % of its final value, where **"e"** is the mathematical constant (e = 2.718281828...). The cut-off frequency depends on the time constant:

$$f_c = \frac{1}{2\pi RC} = \frac{1}{2\pi\tau}, \tag{2}$$

where R is the resistor value, and C - capacitor value. The time constant value was set to τ = 0.001 seconds, obtaining the cut-off frequency $f_c \approx$ 159 Hertz, which corresponds to the angular frequency ω_f = 1000 radians per second.

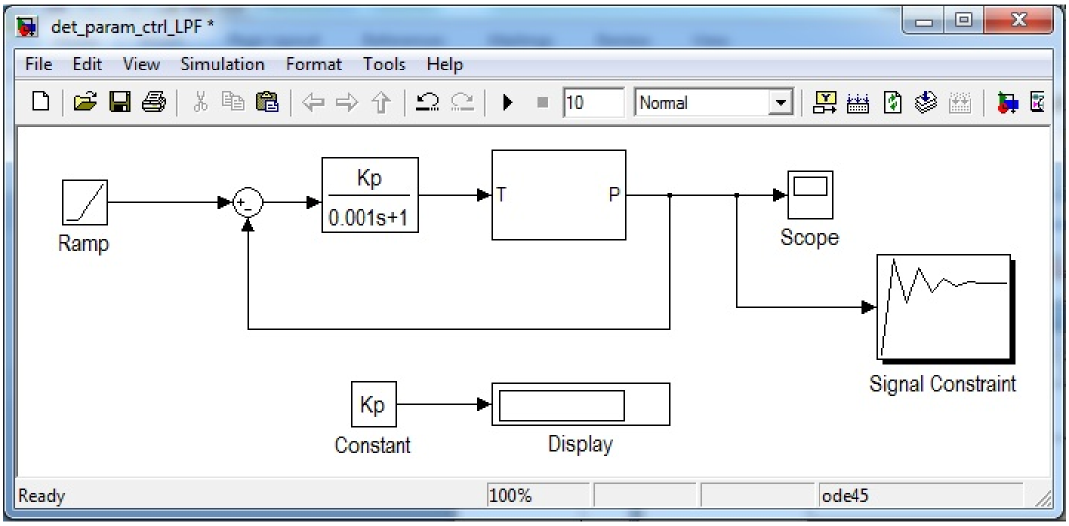

Fig. 5. *The control system for determining the parametres of the controller*

The controller was integrated/connected in the closed-loop control system scheme (Figure 5), the ramp-type excitation signal having a sloping angle of 0.00278, corresponding to the number of degrees covered in one second (according to the motion law mentioned in the beginning of the subchapter). The position controller parametre (amplification factor Kp) was determined with the help of the *Signal Constraint* block, by imposing the following condition: the output signal has to range between two ramp signals, both with a sloping angle of 0.00278, the first one starting from the amplitude of 0, and the second starting from the amplitude of 1. Progressively, this variation interval of the signal is narrowed in order to diminish the steady state error (the difference between the imposed signal and the value the output signal has stabilized at), the simulation time being of 10 seconds, which is enough time to tune the controller.

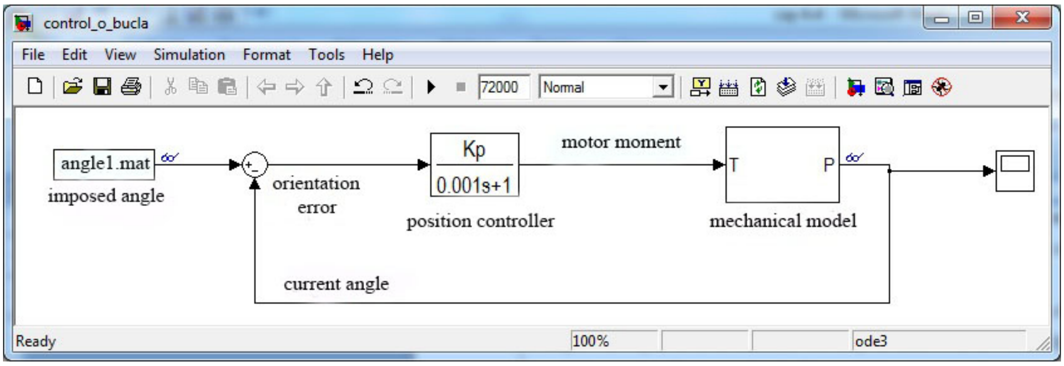

Fig. 6. *Single loop control system model*

For validating/checking the controller, the model in Figure 6 was designed, which integrates a data base (angle1.mat) representing the diurnal position of the system (the imposed diurnal angle - see Figure 4). The control system output is represented by the diurnal angle measured in the revolute joint to the fixed pillar of the photovoltaic module.

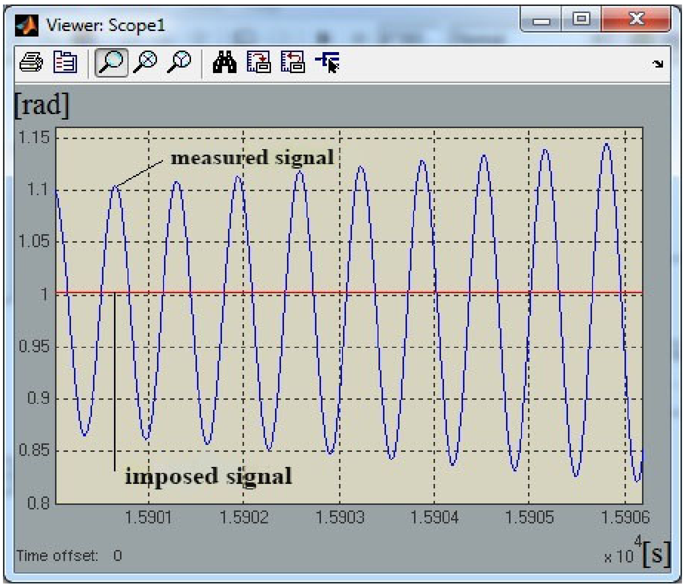

Fig. 7. *Response of a single controlled parameter system*

As seen in Figure 7, the tracking system cannot stabilize, with a very large steady state error. Thus, it is recommended to continue simulations with a two loops control system orientation mechanism (two monitored parametres).

The two loop control system defines a cascade control scheme, whose advantages were previously presented, such as the ability to approach a number of perturbations that influence the process and the improvement of system performance. The two parametres that are to be monitored are the system position (diurnal angle) and the angular velocity of the rotor (Figure 8). The diurnal angle is measured in the revolute joint to the pillar of the photovoltaic module, while the angular velocity is defined in the joint to the stator of the rotor (fixed on the pillar).

The choice/establishing of the monitored parametres follows the necessary requirements for cascading, such as: the dynamics of the secondary loop process (in which the angular velocity of the rotor is monitored/controlled) is faster than that of the primary loop (in which position/diurnal angle is monitored/controlled), because of the spiral shaped rotation decelerator (with a transmission ratio of 50:1); the secondary loop influences the primary loop; the secondary loop is measurable and controllable.

The tuning procedure of the position and velocity controllers (in order to determine amplification factors Kp and Kv) is similar to the one presented for the single control loop model (by using the *Signal Constraint* block).

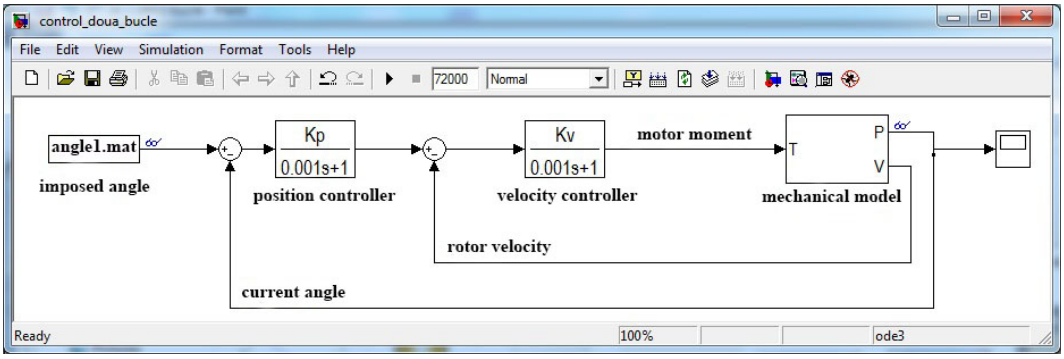

Fig. 8. *The two loop in cascade control system model*

The simulation of the orientation mechanism with a two loop in cascade control system demonstrated that the behaviors of the system is appropriate, with the performance indicators fitting into the optimal/recommended areas. For example, Figure 9 displays the diagrams of the imposed signal and the measured signal respectively for the diuranl angle of the photovoltaic system, for a very short time interval (at the start of the orientation, according to the diagram showing time variation of the diurnal angle in Figure 4), which gives the impression that the imposed signal is constant, but in reality it is slightly raising. It is observable that at the start of the engine the overshoot of the time response is large (however, in acceptable limits), but the steady state errors are very small, which means that the loss of incident radiation (orientation errors) are insignificant.

In conclusion, for the chosen orientation mechanism, in case it is used as an adjusting device of a low-pass filter (LPF) simple controller, the optimal option for control is the one with two loops in cascade, through which the diurnal position of the photovoltaic module is monitored/controlled (in the external/primary loop) and respectively, the angular velocity of the rotor (in the internal/secondary loop).

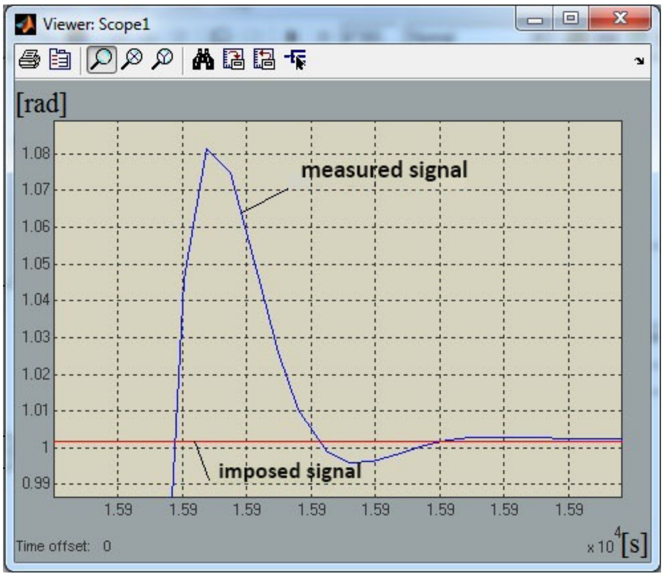

Fig. 9. *Imposed signal and measured signal*

A future study will address the matter of controllers tuning by using the finished virtual prototype of the tracking mechanism. The study will be approached by parametric optimization techniques (DOE - Design Of Experiments) and multiple linear regression, and its objective will be the improvement of the time response (minimizing the overshoot, and the steady state error).

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