ENGINE SPEED CONTROL OF A DIESEL POWER GENERATOR CONVERTED INTO OTTO CYCLE THROUGH CONTROL OF INLET AIR

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ABSTRACT

The electronic throttle valve is the main actuator of the air intake system in Otto cycle engines. The electronic control of this valve at the inlet system allows improved engine performance, fuel economy and exhaust gas reduction with consequent decrease in CO_2, HC and other gases produced by the combustion of hydrocarbons. This article discusses the performance of the engine speed control of an electric power generator set by controlling the angular position of the throttle valve. This engine, the object of this study, was originally from the Diesel cycle and has been adapted for the use in both Diesel and Otto cycles in order to operate with different types of fuels and make it possible to choose the most economically viable. For this work, the focus has been only on the control technique that enabled the engine operation in the Otto cycle. An appropriate cascade control strategy was developed for the system under study and this strategy was validated by experimental tests. The results showed oscillations in the throttle valve response, as a signal above the overshoot of a maximum of 4.0% and an accommodation time-out of 20 seconds. These oscillations are natural due to the dynamics of the throttle valve systems and the internal combustion engine being different. These values meet the demand of the studied system and the presented results of the behavior of the electronic throttle valve demonstrate that it is suitable for use in the electric power generator set.

INTRODUCTION

The electronic throttle valve is a component used to control the flow of air admitted to internal combustion engines. This component is the main actuator of the air intake system of the Otto cycle. The electronic throttle control allows improved engine performance, fuel economy and exhaust gas reduction with consequent decrease in CO_2, HC and other gases produced by the combustion of hydrocarbons. In addition, it allows the application of autopilot techniques, such as cruise control.

Studies on compensators and control strategies applicable to the electronic throttle valve system, for the most part, uses PID (Proportional-Integrative-Derivative) controllers and auxiliary techniques to compensate the system nonlinearity. These techniques consists, in most cases, of robust and adaptive controls. [1].

A nonlinear control strategy uses a proportional, integrative and derivative (PID) controller and a feedback compensator for friction and for instants in which the valve is partially open, known as limp-home (LH). The most relevant effects of friction are the initial delay of response due to the influence of the static friction and the low response time to achieve stability from displacement state. [2].

Another strategy uses a PID controller with advance compensator for limp-home and friction nonlinearities. The output of the controller is a function of the error value and the error derivative. [3]. A nonlinear PID controller can be used in which the output is also set according to the error signal. The particularity of this technique consists in the variation of the output signal according to the variation of the error signal. That results in a longer accommodation time and lower overshoot signal beyond conventional PID controllers. [4].

Unlike a conventional PID controller, it is possible to replace the integrative portion of the error by an arc tangent function of the error. The purpose of this change is to attenuate the effect of the instability generated by the nonlinear discontinuities of some parameters. [5].

It is possible to implement the control of an electronic throttle valve of a hybrid electric vehicle through a PID controller. In which the gains were obtained from a controller tuning method, such as the Ziegler-Nichols method. [6]

An approach to this system can be from a nonlinear controller based on a 3-step method. One for steady-state control, one as an advance compensator, and a PID controller based on the error signal feedback. [7]

An example of an adaptive control strategy is a control composed of a friction compensator and an adaptive controller to deal with the temporal variation of the friction in the system. [8]. Another strategy consists of a proportional-integral-derivative controller (PID) with adaptive gains, an adaptive compensator, and adaptive compensators for friction nonlinearities. Such as from instants where the throttle valve is partially open and the gears backlash. Results were satisfactory, but the ideal situation would be an analysis from the point of view of discontinuous systems. [9]

In addition to the techniques of PID and adaptive controllers, there are still three other approaches to this system. The first is a sliding mode controller in which the position control law is based on the intake system feedback state. The architecture of this control consists of a variable structure and the control action is sliding in the structure based on the throttle valve angular error to measure the unknown operating regions. However, the friction model and spring behavior are simplified and the backlash in the gears is disregarded. [10]. In order to improve the responsiveness of the system and prevent the output signal from exceeding the limit value, an expanded control of the sliding mode control technique has been developed. [11].

The second approach is by neural networks, used by its own ability to characterize complex relationships through a set of memory tests, a nonlinear approximation capability, and learning ability included in its own architecture. A big amount of extremely interconnected processing elements allows the control of specific functions. (ASHOK, DENIS ASHOK, RAMESH KUMAR, 2017).

The neural network adapted in this position control system is based on the systems foundation of the variables to be controlled. A proposal consists of a PID controller that comprises a self-learning system. PID gains varies according to the neural networks indications, which are based on the uncertainties of the system, and by the use of a method that investigates the stability of a nonlinear system through its linearized model (Lyapunov method). [12]. Another proposal of a PID controller, also based on neural networks, showed to be superior in the sense of reference tracing. [13].

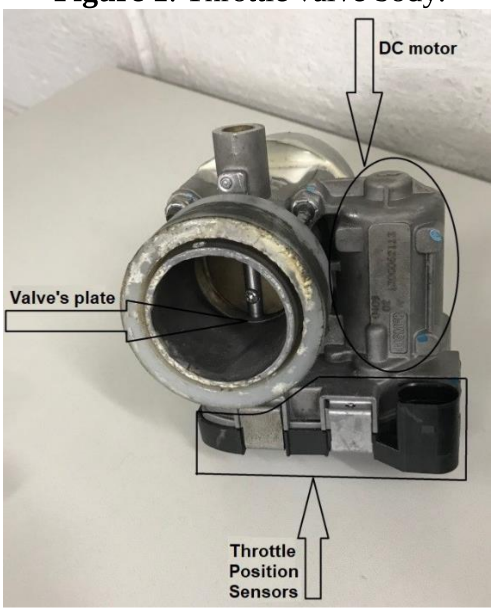
Finally, there is a fuzzy logic technique. Consists in anonlinear control strategy that presents a controller model and an uncertainty compensator. The controller is developed from the linearization of the system, and it is implemented from a fuzzy logic system. [14]. A control strategy with cascaded feedback and fuzzy logic is also used. This control system is composed of a PI - proportional and integrative - discrete controller and a strategy to reduce the overshoot. [15].

In general, the techniques found in the bibliography focus only on the electronic throttle valve position control for original designs of Otto cycle engines. In this perspective, this work approaches the engine speed control of an internal combustion engine coupled to an electric power generator by controlling the electronic throttle valve angular position. For this, a suitable control strategy was developed for the system under study; an analysis of the temporal response of the throttle valve; later, an analysis of the complete system with the behavior of the engine speed and the mass airflow.

1. METHODOLOGY

The throttle valve body consists of a DC motor, a set of gears, return springs, and two potentiometers (Throttle Position Sensors). The electrical signal from these potentiometers defines the angular position of the valve plate. Through another electrical signal the DC motor is activated and applies a torque on the gear set and hence changes the angular position of the valve plate. Once the valve position is changed, the potentiometer signals are also changed. Figure 1 shows the throttle valve body with identification of its main components.

Figure 1: Throttle valve body.



The response of the controlled throttle valve system is nonlinear. Due to the presence of some nonlinearities, a first order polynomial equation cannot describe its angular position. Moreover, there are the influence of the static and dynamic friction, and the behavior of the springs.

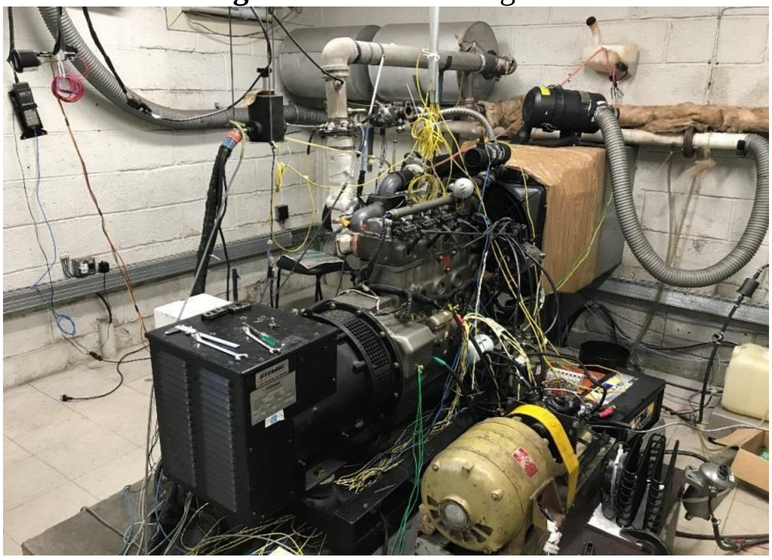
Static friction causes a hysteresis in the throttle valve response when it is leaving or achieving the steady state. Dynamic friction is present when the valve plate is in motion.

The behavior of the springs is linear only on their operating range. To avoid an airflow obstruction and for safety measures in the case of an electrical break, its operation is intensified when the valve is partly open, limp home.

1.1. Experimental methodology

An internal combustion engine, model MWM D229/4, originally from the Diesel cycle, has been adapted for the use in both Diesel and Otto cycles, keeping the original compression ratio. The electronic control of the throttle valve developed enables to switch the engine operation between cycles, but only the Otto cycle operation technique is discussed in this work.

Figure 2: Power set engine.

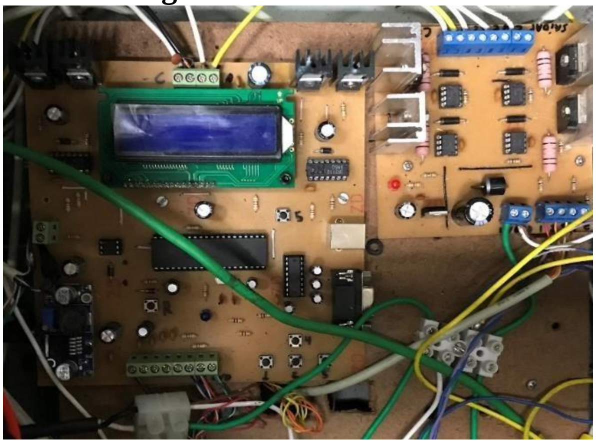


The throttle valve body used in the experiment is from the brand Magneti Marelli (Cod. GTEF0101) and it is present on 1.8 E-torq engines and 1.0 Fire Evo engines, since 2012.

To collect all desired parameters an application has been developed in the *LabVIEW* software. A magnetic reluctance transducer coupled to the phonic wheel collects the engine speed and an absolute pressure transducer (TMAP - Temperature Manifold Air Pressure) collects the mass airflow.

The electronic control consists of a power module and a microcontroller (PIC 18F4550). The driver of the DC motor is an electronic H bridge and a DC voltage signal. This voltage signal is controlled via PWM (Pulse Width Modulation), allowing to change its operation from the duty cycle variation.

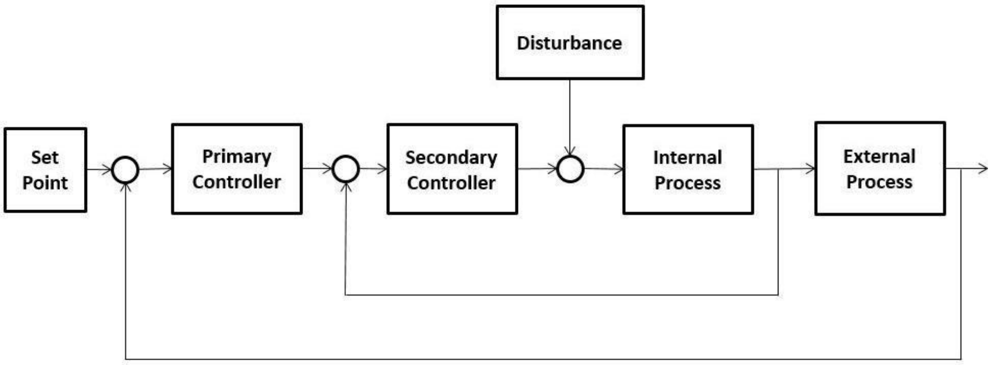
Figure 3: Power module.



1.2. Control Strategy

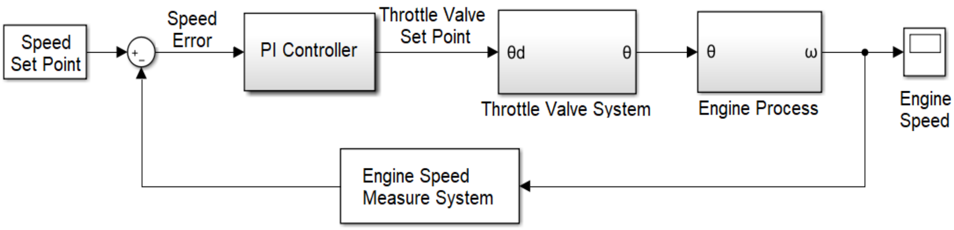
The cascade control strategy is based on the principle that a primary process variable is compared to its desired value. According to the error of the primary process, the reference value of the secondary process is modified. Figure 4 shows a block diagram of the cascade control strategy.

Figure 4: Cascade Control Strategy and its processes.



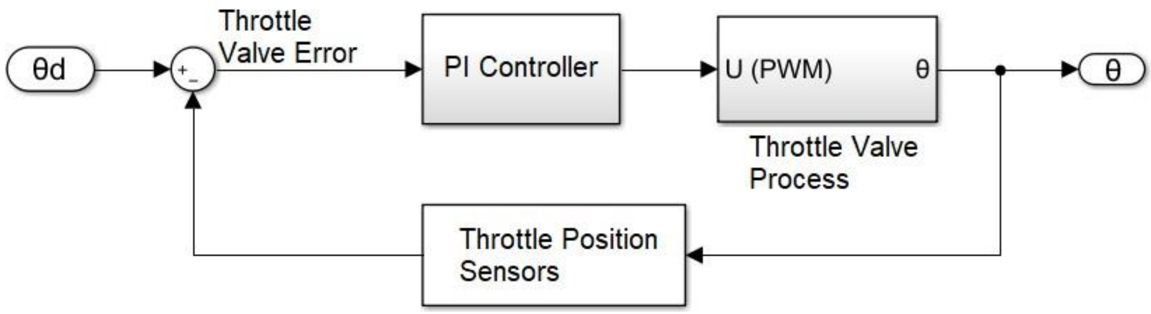
In the proposed strategy on this work, the primary process controls the speed of the internal combustion engine and the secondary process controls the angular position of the throttle valve. Thus, it is possible to divide it into two control systems. Each system presents its own controller and, in both cases, the controller used is a proportional and integrative (PI). Figure 5 shows the primary control process.

Figure 5: Process of the internal combustion engine speed control.



Considering the secondary process as a position control, it is possible to assert that its ideal gain is unitary so that the desired angle is equal to the output angle. Is also important to notice that the positioning system has a faster response time than the external process. This ensures that the system can adjust any disturbance on the throttle valve before it influences the primary process. Figure 6 shows the position control process of the throttle valve.

Figure 6: Process of the throttle valve angular position control.



The feedback of the internal process is generated from the electrical signals of the valve body potentiometers. Then the external loop feedback is defined as the speed measurement system, being performed by a frequency signal from an inductive sensor positioned on the phonic wheel. The processing of this signal is made by a micro controller, which performs the acquisition of the measured speed value.

1.3. Procedures

In the Otto cycle the motor-generator group was fueled with Hydrated Ethanol. Three series of tests were carried out with variable loads applied to the motor according to the Table 1:

Table 1: Load series.

SERIE	ROUTINE OF LOADS [kW]
1	0,0 – 5,0 – 10,0 – 15,0 – 20,0 – 22,5 – 25,0 – 27,5 – 25,0 – 22,5 – 20,0 – 15,0 – 10,0 – 5,0 – 0,0
2	0,0 – 5,0 – 10,0 – 15,0 – 20,0 – 25,0 – 27,5 – 25,0 – 20,0 – 15,0 – 10,0 – 5,0 – 0,0
3	0,0 – 10,0 – 20,0 – 27,5 – 20,0 – 10,0 – 0,0

Each routine was repeated three times, keeping 2 minutes in each load, in order to guarantee the stability and repetitiveness of the data. The values of: reference value of the throttle valve angle defined by the control system, the actual throttle valve angle, the engine speed, the load applied and the airflow admitted were collected.

2. RESULTS AND DISCUSSIONS

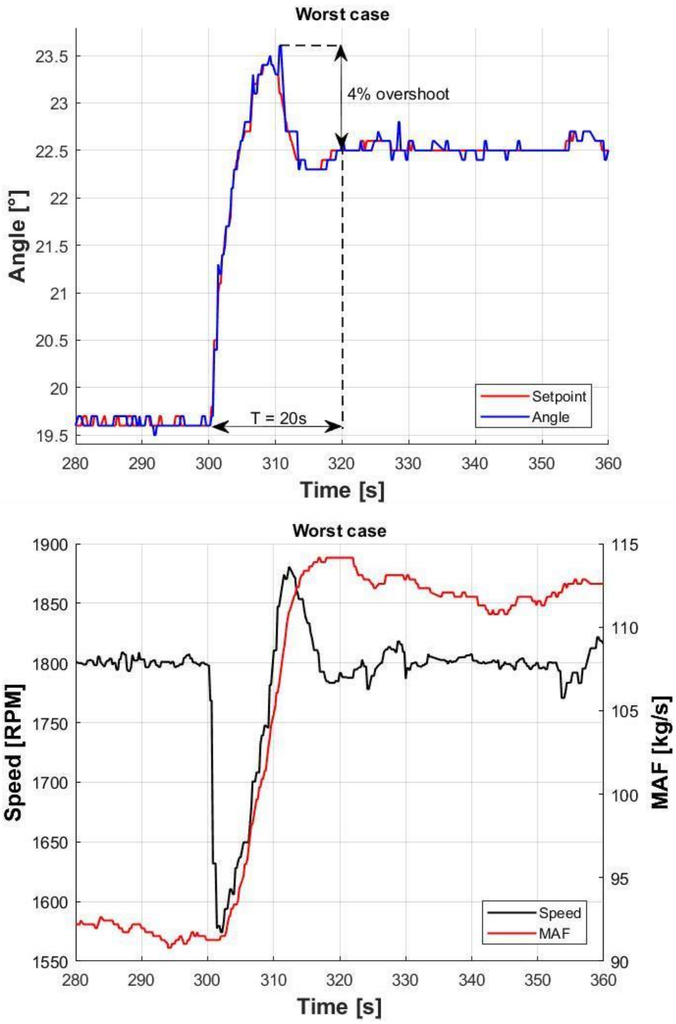
Previous works developed an approach focused on applicable techniques to deal with the electronic throttle valve nonlinearities. [1], [16].

The strategy that uses a PID controller coupled with methods designed to deal with nonlinearities [2]–[4], [7] is the most similar to this study. However, a simulation of the throttle valve angular response is most common approach to present results.

The focus of this work is to investigate the response of the electronic throttle valve, coupled in a power engine set system. Thus, the time bands were defined according to each specific change on load. Based on accommodation time and throttle valve response overshoot, we had chosen a better case, an intermediate case, and a worst case.

The worst case was defined as the increasing transition between 20 kW and 27.5 kW of the 3rd series of tests. Figure 7 shows the angular variation for this load transition and the response of the engine speed and the Mass Air Flow (MAF).

Figure 7: Response of the throttle valve, engine speed and airflow.



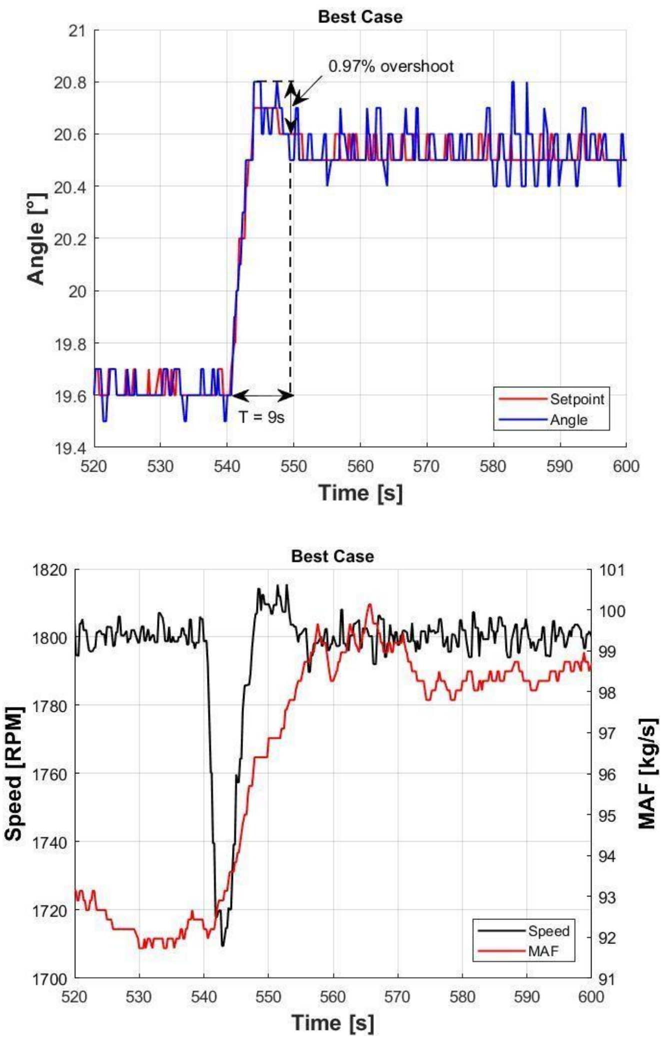
From the desired angular position for the load of 27.5 kW (approximately 22.5°), it can be seen that the throttle valve response has been well aligned with the reference value variation. The maximum overshoot is 1.0° (4.0%) and the accommodation time is approximately 20 seconds. Following, the engine speed response also showed an overshoot in the order of 4%, that is, 80 rpm. After the increasing load transition, we can observe a speed decrease of 10%. It is due to the absence of a predictive control for situations of increasing power demand.

The relation between the throttle valve angular position, the speed and the mass airflow can explain the characteristic of the mass airflow response. As the throttle valve opens, the availability of air increases, but does not mean into an instantaneous increase of airflow. Due to the larger throttle valve opening there is a tendency of poor mixture, so the system operates by injecting more fuel to maintain the air-fuel ratio. This results in an increased speed and consequently increased airflow.

As soon as the load was changed to 27.5 kW (t = 300 seconds) the valve reference value variation occurred in approximately 0.5 seconds. Besides, the increase of the airflow and the increase of the speed are perceived after approximately 2.0 seconds. This difference in response time is justified by the difference on the dynamics of a position control system and a engine speed control system. The throttle valve system is electronic and the power engine system is mechanical. Naturally, the mechanical system response is slower.

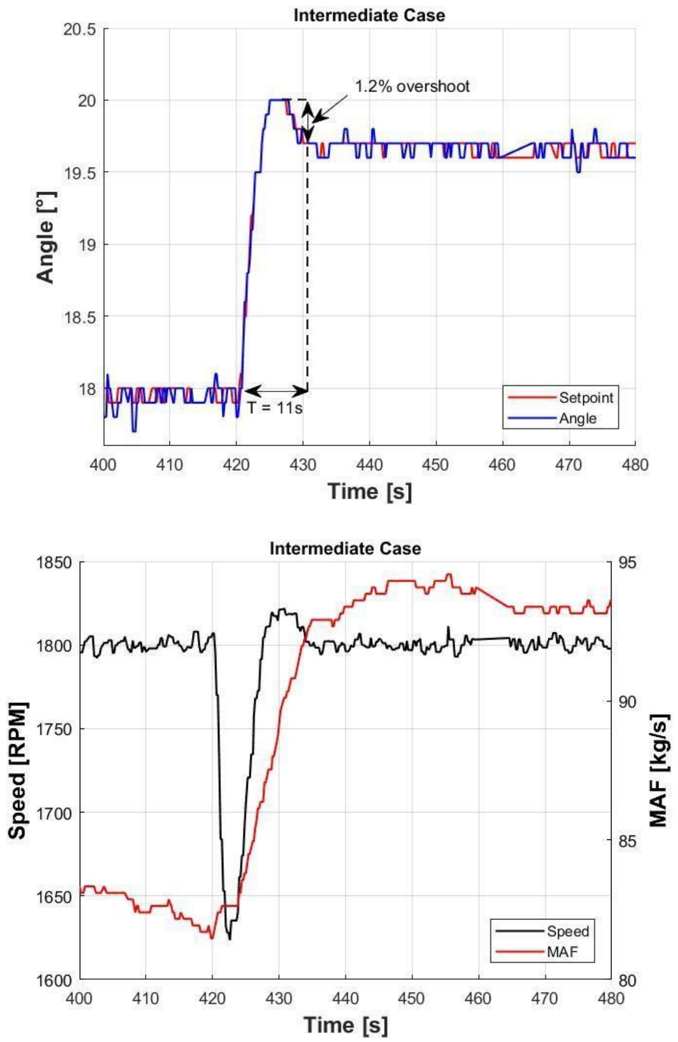
The best case was defined as the increasing transition between 20 kW and 22.5 kW from the 1st series of tests. Moreover, the intermediate case was defined as the increasing transition between 15 kW and 20 kW, also from the 1st series of tests. Can be noted that the behavior of the throttle valve angular variation, the power engine speed and the MAF were correspondent to those of the transition from 20 kW to 27.5 kW. Figures 8 and 9 present these results.

Figure 8: Throttle valve angular position, engine speed, and airflow at the best case.



It can be observed that, in the best case, the throttle valve angular position overshoot was approximately 0.2° (0.97%) and the accommodation time was approximately 9 seconds. For the engine speed, the overshoot was 15 rpm (0.8%).

Figure 9: Throttle valve angular position, engine speed, and airflow at the intermediate case.



At the intermediate case the angle overshoot was approximately 0.4º (2.0%) and the accommodation time was approximately 11 seconds. For the engine speed, the overshoot was 22 rpm (1.2%).

3. CONCLUSIONS

The analyzed electronic throttle valve system is suitable for use in the power engine set.

The oscillations found on the throttle valve are acceptable since the response time has proved appropriate for the stable operation of the power engine set. Consequently, some variations in the speed were also observed. By virtue of the cascade control strategy and the slower response of the mechanical system, such variations can be considered admissible.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the following agencies: CNPq, CAPES, and FAPEMIG.

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