Buletinul Ştiinţific al Universităţii Politehnica Timişoara

TRANSACTIONS on ELECTRONICS and COMMUNICATIONS

Volume 59(73), Issue 1, 2014

Modeling in Matlab/Simulink the control of the vehicle's air conditioner compressor

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Abstract – This article presents a model developed in MATLAB/SIMULINK, for the control of the vehicle's air conditioner compressor with a PWM signal. This signal is used to control the solenoid valve of the compressor. The model was created to allow in the future the study of the compressor's behavior in different operating conditions of the vehicle to improve the functioning of the internal combustion motor and optimize the efficiency of the air conditioner system. The model will be converted to a software script to be used in the car together with the AutoBox from dSpace.

Keywords: air conditioner, compressor, model, AutoBox, dSpace

I. INTRODUCTION

Air conditioning systems have long ceased to be regarded as luxury equipment. Air conditioners have become a factor in active safety, and today can almost be considered as an integral part of a vehicle's safety specification. 10 years ago, only about 10 percent of all newly registered vehicles were fitted with an air conditioning system. By 1996, air conditioners were being installed as standard in more than one in four newly registered vehicles. The design of the refrigerant circuit of an air conditioner is identical in all vehicles. Air conditioner refrigerant circuits only vary in respect of how they are adapted to meet refrigeration requirements, [1].

People feel comfortable at a certain ambient temperature and atmospheric humidity. As a component part of active safety, the driver's well-being is a key factor in driving ability. The "in-car climate" has a direct bearing on the driver, fatigue-free driving and driving safety. A comfortable interior temperature is dependent upon the prevailing ambient temperature and upon sufficient air flow:

Low ambient temperature, e.g. -20 °C

❖Higher interior temperature 28 °C
High air flow rate: 8 kg per min.

High ambient temperature, e.g. 40 °C

❖Low interior temperature 23 °C
High air flow rate: 10 kg per min.

Modarate ambient temperature, e.g. 10 °C

❖Low interior temperature 21.5 °C
Low air flow rate: 4 kg per min

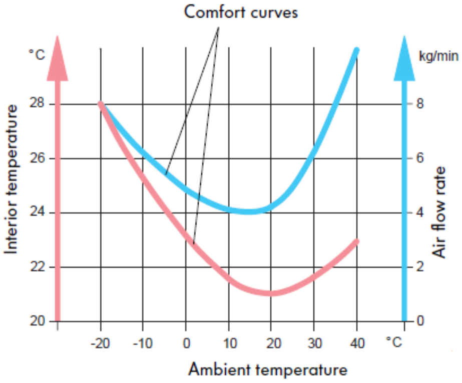
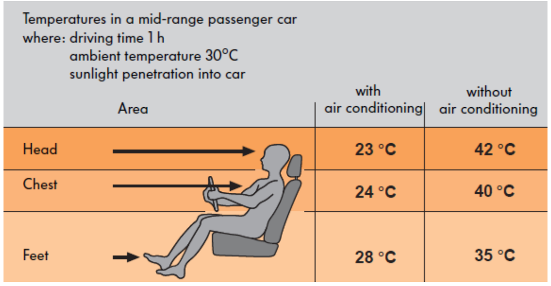


Fig. 1. The interior temperature and the air flow rate depending on the ambient temperature



Temperatures in a mid-range passenger car
where: driving time 1 h
ambient temperature 30°C
sunlight penetration into car

Area	with air conditioning	without air conditioning
Head	23 °C	42 °C
Chest	24 °C	40 °C
Feet	28 °C	35 °C

Fig. 2. The interior temperature with and without the air conditioning

Even modern heating and ventilation systems have difficulty maintaining a pleasant climate inside a vehicle at high ambient temperatures. In strong sunlight in particular, the heated cabin air can only be exchanged for air with ambient temperature. In addition, the air temperature usually rises on route from the intake point to the air outlet. Opening a window or sliding roof or setting a higher fan speed for greater comfort will usually result in a draught and expose the occupants to other nuisances such as noise, exhaust gases and pollen, [1].

High levels of atmospheric humidity put the body under considerably greater physical strain.

Scientific studies conducted by the WHO (World Health Organization) have shown that one's ability to concentrate and reactions are impaired when under

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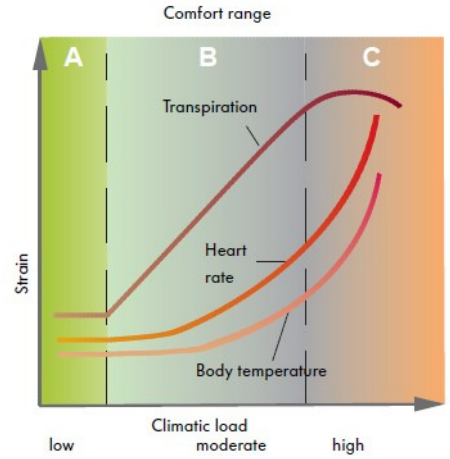

Fig. 3. Comfort range

stress. Heat puts a strain on the body. The best temperature for the driver is between 20 and 22 °C. This is equivalent to climatic load A (see Fig.3), the "comfort range".

Strong sunlight can increase the interior temperature by more than 15 ℃ above the ambient temperature particularly in the head area. This is where the effects of heat are most dangerous. The body temperature rises and the heart rate increases. Heavier perspiration will typically occur, too. The brain is not receiving enough oxygen. Also refer to "climatic load range B". Climatic loads in range C put an excessive strain on the body. Physicians specializing in traffic-related illnesses refer to this condition as “climatic stress”, [1].

Studies have shown that an increase in temperature from 25 to 35 °C reduces one's sensory perception and powers of reasoning by 20%. It has been estimated that this figure is equivalent to a blood alcohol concentration of 0.5 milliliters alcohol level.

II. THE REFRIGERANT

The refrigerant with a low boiling point used for vehicle air conditioners is a gas. As a gas, it is invisible. As a vapour and as a liquid, it is colorless like water. Refrigerants may not be combined with each other. Only the refrigerant specified for the system in question may be used. [1]

With regard to vehicle air conditioners, the sale and filling of refrigerant R12 were banned in Germany with effect from 1995 and July 1998 respectively.

In current automotive air conditioners, only refrigerant R134a is used. R134a, a fluorocarbon contains no chlorine atoms, unlike refrigerant R12, which cause depletion of the ozone layer in the earth's atmosphere when they split. The vapour pressure curves of R134a and R12 are very similar. R134a has the same refrigeration capacity as R12. Depending on the pressure and temperature conditions in the refrigerant circuit, the refrigerant will either be a gas or a liquid.

Table 1

Parameter	Value	Unit
Boiling point	-26.5	℃
Freezing point	-101.6	℃
Critical temperature	100.6	℃
Critical pressure	4.056/40.56	MPa/bar

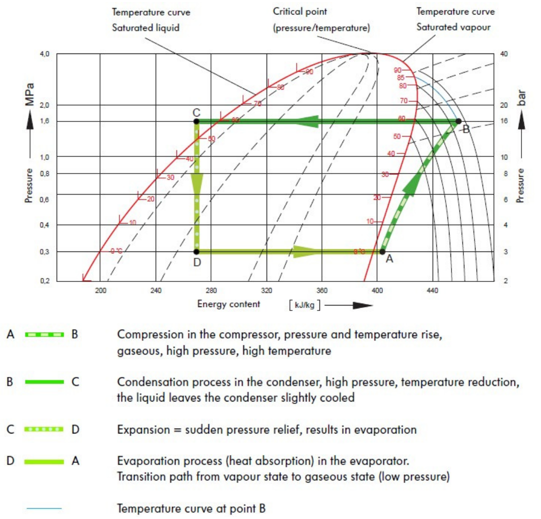

Fig. 4. The cycle in an airconditioner

In addition to the vapour pressure curve, the cycle shows the change of state of the refrigerant under pressure and temperature in addition to the energy balance at which the refrigerant returns to its original state. The diagram is an excerpt from the state diagram of refrigerant R134a for a vehicle air conditioner. Different absolute values are possible in dependence upon the demand of a vehicle type for refrigeration capacity.

The energy content is a key factor in the design of an air conditioner. It shows what energy is required (evaporator heat, condenser heat) to achieve the intended refrigeration capacity.

Ozone protects the earth's surface against UV radiation by absorbing a large proportion of these rays. UV rays split ozone (O_3) into an oxygen molecule (O_2) and in an oxygen atom (O). Oxygen atoms and oxygen molecules from other reactions combine again to form ozone. This process takes place in the ozonosphere, a part of the stratosphere at an altitude of between 20 and 50 km.

III. THE COOLING SYSTEM

We know that too cool down an object, heat must be given off. A compression refrigeration system is used in motor vehicles for this purpose. A refrigerant circulates in the closed circuit, continually alternating changing from a liquid to a gas and vice versa. The refrigerant is:

- compressed in the gaseous state
- condensed through heat dissipation
- evaporated through pressure reduction and heat absorption.

Cool air is not produced, heat is extracted from the air flow in the vehicle.

The compressor induces cold, gaseous refrigerant at a low pressure. The refrigerant is compressed in the compressor, causing it to heat up. The refrigerant is pumped into the circuit on the high-pressure side.

The compressed liquid refrigerant continues to flow up to a narrowing. This narrowing can be in the form of a restrictor or an expansion valve. Once the refrigerant reaches the narrowing, it is injected into the evaporator causing its pressure to drop (low-pressure side).

Inside the evaporator, the injected liquid refrigerant expands and evaporates. The evaporation heat required for this purpose is extracted from warm fresh air which cools down when it passes through the evaporator fins. The temperature inside the vehicle is reduced to a pleasant level.

The components from figure 5 are as follows:

A Compressor with magnetic clutch
B Condenser
C Fluid container with drier
D High pressure switch
E High pressure service connection
F Expansion Valve
G Evaporator
H Low pressure service connection
I Damper (vehicle specific

The refrigerant follows the short path to the condenser (liquefier). Heat is now extracted from the compressed, hot gas in the condenser by the air flowing through (headwind and fresh air blower). The refrigerant condenses and becomes a liquid when it reaches its melting point (pressure dependent), [1].

Now in the gaseous state again, the refrigerant emerges from the evaporator. The refrigerant is again drawn in by the compressor and passes through the cycle once again. Thus, the circuit is closed.

The refrigeration capacity of a vehicle air conditioner is dependent upon the car-specific installation conditions and the vehicle category (passenger cars, vans). The components A to H exist in every circuit.

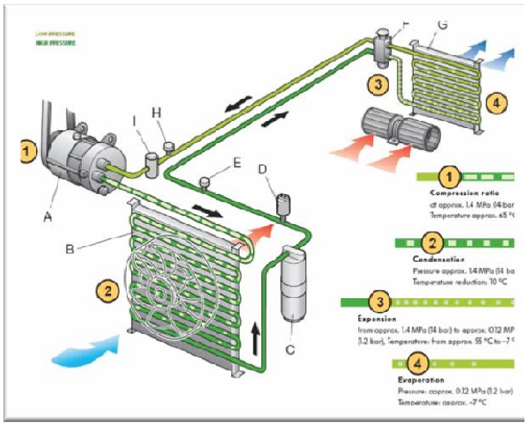

Fig. 5. The air conditioner circuit with expansion valve

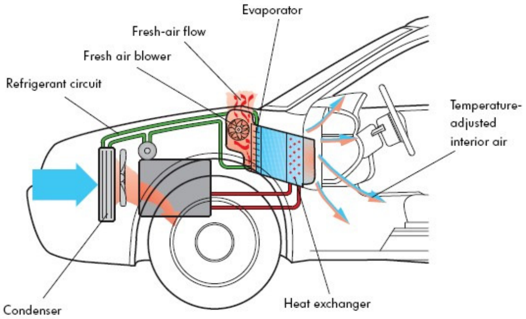

Fig. 6. Localization of the refrigerant circuit in the car

Additional connections can be provided for service work, temperature sensors, pressure switches in the high- and low-pressure circuit and oil drain screws depending on the circuit design and requirements. The layout of components within the circuit also differs from one vehicle type to another. Some systems have a damper before the compressor in order to dampen refrigerant vibrations.

The pressures and temperatures in the circuit are always dependent on momentary operating state. The specified values are intended as a rough guideline only. They are reached after 20 min. at an ambient temperature of 20 ℃ and at engine speeds of between 1500 and 2000 rpm. At 20 ℃ and when the engine is at a standstill, a pressure of 0.47 MPa (4.7 bar) will build up inside the refrigerant circuit.

IV. THE COMPRESSOR

The compressors used in vehicle air conditioners are oil-lubricated displacement compressors. They operate only when the air conditioner is switched on, and this is controlled by means of a magnetic clutch. The compressor increases the pressure of the refrigerant. The temperature of the refrigerant rises at the same time. Were there to be no pressure increase, it would not be possible for the refrigerant in the air conditioner to expand and therefore cool down subsequently. A special refrigerant oil is used for lubricating the compressor. About half of it remains in the compressor while the other half is circulated with the refrigerant. A pressure shut-off valve, which is usually attached to the compressor, protects the system against excessively high pressures, [1].

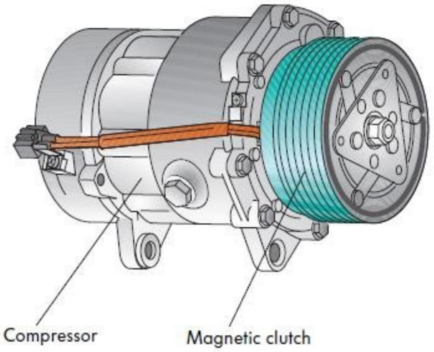

Fig. 7. Compressor with magnetic clutch

The compressor draws in cold, gaseous refrigerant through the evaporator under low pressure. It is "vital" for the compressor that the refrigerant be in a gaseous state, because liquid refrigerant cannot be compressed and would destroy the compressor (in much the same way as a water shock can damage an engine). The compressor compresses the refrigerant and forces it towards the condenser as a hot gas on the high-pressure side of refrigerant circuit. The compressor therefore represents the interface between the low-pressure and high-pressure sides of the refrigerant circuit.

Compressors for air conditioners operate according to various principles:

- Reciprocating compressors
- Coiled tube compressors
- Vane-cell compressors
- Wobbleplate compressors

The turning motion of the input shaft is converted to an axial motion (= piston stroke) by means of the wobbleplate. Depending on compressor type, between 3 and 10 pistons can be centred around the input shaft. A suction/pressure valve is assigned to each piston. These valves open/close automatically in rhythm with the working stroke. An air conditioner is rated for the max. speed of the compressor. However, the compressor output is dependent on engine rpm. Compressor rpm differences of between 0 and 6000 rpm can occur. This affects evaporator filling as well as the cooling capacity of the air conditioner. Controlled-output compressors with a variable displacement were developed in order to adapt compressor output to different engine speeds, ambient temperatures or driver-selected interior temperatures.

Compressor output is adapted by adjusting the angle of the wobbleplate. In constant-displacement compressors, compressor output is adapted to the demand for refrigeration by switching the compressor on and off periodically via the magnetic clutch.

All control positions between upper stop (100 %) and the lower stop (approx. 5 %) are adapted to the required delivery rate by altering the chamber pressure. The compressor is on continuous duty during the control cycle.

The turning motion of the input shaft is transmitted to the drive hub and converted to axial motion of the piston via the wobbleplate. The wobbleplate is located longitudinally in a slide rail. The piston stroke and the delivery rate are defined by the inclination of the wobbleplate.

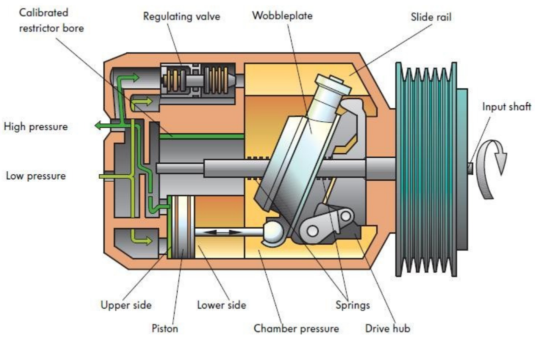

Fig. 8. Compressor

Inclination - dependent on the chamber pressure and hence the pressure conditions at the base and top of the piston. The inclination is supported by springs located before and after the wobbleplate.

Chamber pressure - is dependent upon the high and low pressures acting upon the regulating valve and by the calibrated restrictor bore.

High pressure, low pressure and chamber pressure are equal when the air conditioner is off.

The springs before and after the wobbleplate set it to a delivery rate of about 40%. The advantage of output control is that it eliminates compressor cut-in shock, which often manifests itself in a jolt while driving.

V. THE CONTROL COMPRESSOR MODEL

In the first part of the description is presented the model implemented in SIMULINK. Simulink is a block diagram environment for multidomain simulation and Model-Based Design. It supports system-level design, simulation, automatic code generation, and continuous test and verification of embedded systems. Simulink provides a graphical editor, customizable block libraries, and solvers for modeling and simulating dynamic systems. It is integrated with MATLAB, enabling you to incorporate MATLAB algorithms into models and export simulation results to MATLAB for further analysis, [2].

This model was created for the control of the vehicle's air conditioner compressor with a PWM signal. This signal is used to control the solenoid valve of the compressor. After the model is developed, it used to be uploaded to the ControlDesk. The model will be compiled on the PC and the resulting script is loaded on an AutoBox from dSPACE and the results are then shown both on the ControlDesk and on the oscilloscope. AutoBox is the ideal environment for using your dSPACE real-time system for in-vehicle control experiments such as test drives for powertrain, ABS or chassis control development. You can install AutoBox anywhere in a vehicle, for example, in the trunk of your test car.[5] On the AutoBox we have the DS2201 board which will be used in the project. The DS2201 Multi I/O Board provides a space-saving solution for applications requiring a lot of I/Os, [6].

The model implemented in SIMULINK is based on the schematic shown in figure 10. Same as other types

Fig. 9. The Autobox

of AC compressors, the externally controlled one essentially needs to compress AC refrigerant. The pressurized refrigerant flows through condenser where it can be cooled down by the engine cooling fan and/or vehicle movement. This subsequently reduces pressure to certain level. The refrigerant passes through TxV (thermostat expansion valve) where the expanded refrigerant becomes cool. The cooling is then brought away by the air through the evaporator. The cooled air from evaporator is then produced for cabin cooling and dehumidification. Externally controlled compressor has two controllable parts, namely clutch and control valve. The same as internally controlled compressor and fixed displacement compressor, the AC clutch can make the compressor fully turning and fully stopping. The engagement of the clutch makes compressor switching on (turning) and the disengagement makes compressor switching off (stopping). The compressor is driven by engine crankshaft via pulley. The control valve makes the compressor be called 'Externally controlled' which adds more control ability than other used compressors. The valve is installed between 3 chambers inside the compressor, e.g. discharge, suction and crankcase. The fully open/close of the valve can make the passage available between discharge and crankcase chambers or between crankcase and suction chambers (depends on suppliers). The valve is a solenoid driven. A PWM signal is to deliver required control current on the valve solenoid. The current level is corresponding to the valve open position which consequently determines the suction pressure that can be maintained at steady-state. There is also a bleeding passage between crankcase and suction chambers. That makes crankcase pressure tend to equalize to suction pressure. The pressure levels in the three chambers and compressor turning speed determines the position of the swash plate that results in different compressor piston displacement. The displacement will give rise to different compressor capacity and different torque loss.

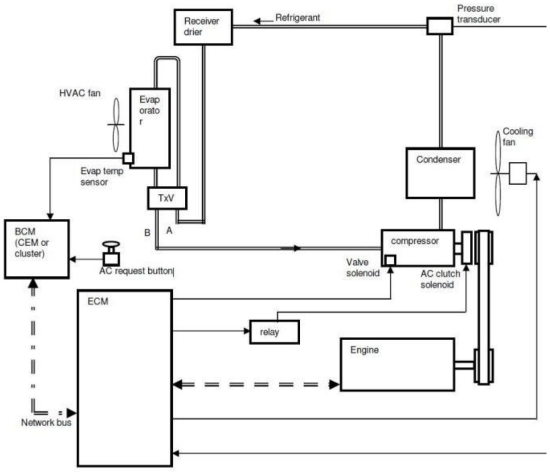

Fig. 10. Compressor

The model uses some inputs signals which are calibrated in order to avoid malfunctions for the vehicle's motor and for the mechanical components in the circuit of the air conditioner. These inputs are: the ambient temperature, the activation ratio of accelerator pedal, the engine speed, the coolant temperature, the refrigerant pressure for the air conditioner compressor, the evaporator temperature and the time after start.

For the critical switch of conditions such as critical engine speed, defective fan, critical cooling pressure, critical cooling temperature or critical ambient temperature, it is used a minimum turn-on time and a minimum turn-off time.

If the vehicle has climate control module which can create an evaporator temperature set point, then ECU will use the evaporator temperature set point signal in the close loop controller. Otherwise, ECU needs to create the evaporator temperature set point according to a calibrated table based on ambient temp.

The AC valve duty cycle must be obtained from a PID controller with input of the difference between evap temp and evap temp set point. The PID controller is the most common controlling algorithm based on system feedback form. The "textbook" version of the PID algorithm is described by:

$$u(t) = K\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d\frac{de(t)}{dt}\right) \qquad (1)$$

where y is the measured process variable, r the reference variable, u is the control signal and e is the control error ($e = y_{sp} - y$). The reference variable is often called the set point. The control signal is thus a sum of three terms: the *P* term, (which is proportional to the error), the *I* term (which is proportional to the integral of the error), and the *D* term (which is proportional to the derivative of the error). The controller parameters are proportional gain *K*, integral time T_i, and derivative time T_d. The integral, proportional and derivative part can be interpreted as control actions based on the past, the present and the future, [3].

During idle, the result of the evap temp closed loop controller should be restricted by an extra regulator.

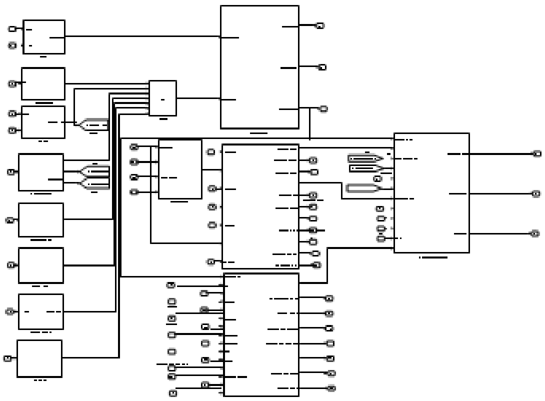

Fig. 11. The model

If demanded torque is smaller than a lower threshold, then the duty cycle obtained from the evap temp closed loop controller should be directly used. The lower threshold is the product of max available torque and a calibrated factor.

If demanded torque is greater than an upper threshold, then a valve duty cycle increment should be used. The increment is obtained from a calibrated table as a function maximum available torque. The upper threshold is the product of max available torque and another calibrated factor.

If engine is in launch operation, then the AC compressor should work at a degraded condition or disengage AC clutch. At transition of A/C clutch engagement to disengagement due to launch cut-out, initialized cut-out timer starts decrementing.

If there is any request to minimize the AC valve duty cycle for any function, then the valve duty cycle should be firstly minimized to a calibrated level. If AC clutch is disengaged for AC off request, then the valve duty cycle should also be minimized.

The model will be then compiled and for optimization, the model was simulated with a single step, discret, and with the ode 5 solver. After the simulation there were generated o series of files with different extensions, from them de .sdf file was used.

First part of the experiment in ControlDesk is to create a project for which the .sdf file from the Simulink model, will be used. For visualization and controlling the desired parameters the a .lay file will be used, after this we can use different instrument like controllers, indicators, plotters etc. In figure 12, we have a GUI made in the ControlDesk, the interface presents the inhibitions from the model in Simulink, respectively the ambient temperature, the activation ratio of accelerator pedal, the engine speed, the coolant temperature, the refrigerant pressure for the air conditioner compressor, the evaporator temperature and the time after start.

In the last part of the experiment, the PWM signal from the model is present on one pin from the DS2201 board on the AutoBox. The signal can be seen on the oscilloscope, as shown in figure 13. In order to see the signal on the DS2201 board we have to use the dSPACE RTI1005 library in the Simulink model. This library consits of : I/O units for ADC, DAC convertors, digital I/O, signal generation and frequency measurements. Real-Time Interface (RTI) is the link between dSPACE hardware and the development software MATLAB/Simulink/Stateflow from The MathWorks, [7].

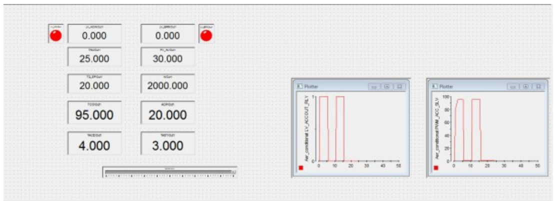

Fig. 12. The GUI from ControlDesk

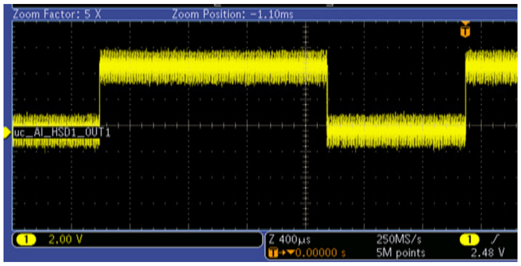

Fig. 13. The PWM signal on the osciloscope

VI. CONCLUSION

The model was developed for the control of the vehicle's air conditioner compressor using a PWM signal. The AutoBox from dSPACE together with the ControlDesk helps us represent the signal in Real Time.

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