A MATLAB-BASED APPROACH FOR CONTROL SYNTHESIS OF DC-DC CONVERTERS

Bogdan Gilev (1), Nikolay Hinov (2), Kiril Genev (2)*

(1) Faculty of Applied Mathematics and Informatics, Technical University of Sofia;
(2) Faculty of Electronic Engineering and Technologies, Technical University of Sofia, Bulgaria

* Corresponding Author, e-mail: hinov@tu-sofia.bg

Abstract: The main steps of the synthesis of the control of DC-DC converters based on Matlab are discussed in the manuscript. Shown is the implementation and setup of 3 types of controllers used in a specific example Boost DC-DC converter: classic PID, neural network, and Fuzzy. For some of the cases, the source code is also given, thus the examples presented are useful both for the purposes of training in power electronics and for the specialists-designers of power electronic devices.

Key words: control synthesis, DC-DC converters, Matlab, power electronic device design, resonant inverters.

1. INTRODUCTION

Improving the performance of power electronic devices is key to increasing the efficiency, reliability, and durability of electronic power flow control systems [1]. The main strategies and techniques to improve the performance of these devices are as follows:

1. Optimization of thermal management

- Cooling Improvement: The use of efficient cooling systems (both passive and active) can significantly increase the efficiency and reliability of power electronic devices. Improvements can include advanced heat sink materials, fans, heat exchangers, and liquid cooling.

- Thermal design of the printed circuit board (PCB): Optimizing the PCB design for better heat dissipation can reduce the risk of overheating.

2. Use of materials with high performance and better qualities compared to classic ones.

Power semiconductors: The use of silicon carbide (SiC) and gallium nitride (GaN) devices can improve efficiency and reduce losses in power electronic devices as they operate efficiently at higher temperatures, voltages and frequencies.

3. Improvement of control algorithms [2,3]

Adaptive and intelligent control: Developing control algorithms that can adapt to changing operating conditions and optimize performance in real time (such as using artificial intelligence and machine learning) can significantly improve efficiency and reliability.

4. Electromagnetic compatibility (EMC)

EMC improvement: Developing devices that reduce electromagnetic interference can improve their performance and reduce the risk of unwanted interactions with other equipment.

5. Optimization of schemes

Efficient design: Optimizing circuits to reduce conduction and switching losses by evaluating the current path and avoiding long wires that can increase inductance and losses.

6. Reliability and durability

Reliability tests: Conducting extensive reliability tests, including thermal cycle, vibration and shock tests, can help identify potential weak points and improve the longevity of devices.

7. Software optimization

Firmware and software: Developing optimized software and firmware that effectively manages the operations of power electronic devices can greatly improve their efficiency and responsiveness.

Improving the performance of power electronic devices requires an integrated approach that includes not only hardware, but also software optimizations, as well as continuous attention to the latest technological developments and materials. In this sense, the synthesis of control of power electronic devices covers the development and application of methods and algorithms for control of electronic components that regulate and convert electrical energy in power supply systems [4,5]. This can include a wide range of devices such as frequency converters, inverters, rectifiers and voltage regulators. The goal of control synthesis is to provide efficient, reliable and accurate control of these devices, taking into account their dynamic characteristics and their interaction with the electrical network.

The main components of synthesis management are the following:

- Modeling and analysis: The first step in control synthesis is the development of accurate mathematical models of the power electronic devices. This includes analysis of their electrical, thermal, and mechanical characteristics.
- Control Algorithms: Various control algorithms are developed, which can be linear or non-linear, depending on the application and desired system characteristics. Methods such as PID controllers (proportional, integral, differential), vector control, direct torque control, etc. are often used.
- Digital Control: With the growing popularity of microcontrollers and DSP (Digital Signal Processors), digital control is becoming the primary method for implementing control algorithms. It allows high accuracy, flexibility, and easy integration with other systems [6].
- Simulation and optimization: Prior to physical implementation, algorithms and control systems are tested and optimized through computer simulations. Specialized software packages such as MATLAB/Simulink, PLECS and others are used [7].
- Communication protocols: In modern energy systems, power electronic devices often need to communicate with each other and with central control systems. Appropriate

communication protocols such as CAN, Modbus, Ethernet, etc. are developed and integrated.

The subject of the present work is the presentation of a Matlab-based approach for the synthesis of control of DC-DC converters.

2. MODELING OF A DC-DC BOOST (STEP-UP) CONVERTER

The power diagram of a step-up DC-DC converter is shown in Fig.1. It is composed of a transistor, diode, and filter elements.

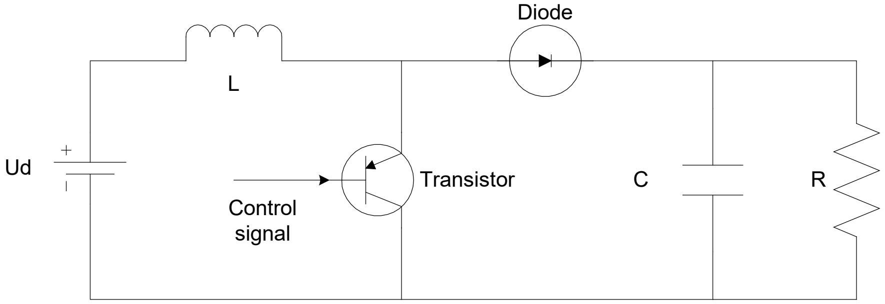


Figure 1. Classic DC-DC boost converter

When designing using known design methodologies, the following circuit parameters were obtained: Ud=20 V - input voltage, R=10 Ω - load resistance, C=10 μF - filter capacitance and L=15 mH - filter inductance. The control signal of the transistor has a period T=1/100000 s and a duty cycle D=0.7. The state variables are the i-current through the inductance and the u-voltage across the capacitor.

The converter is modeled with a system of ordinary differential equations (ODE) and a switching function F, i.e.

$$\left| \begin{array}{l} L\dfrac{di}{dt}+u(1-F)=U_d \\ C\dfrac{du}{dt}+\dfrac{u}{R}=i(1-F) \end{array} \right. \text{, where } F=\begin{cases} 1-\text{transistor on} \\ 0-\text{transistor off} \end{cases} \tag{1}$$

The model (1) is transformed into a matrix form and acquires the form:

$$\begin{pmatrix} L\dfrac{di}{dt} \\ C\dfrac{du}{dt} \end{pmatrix}=\begin{pmatrix} 0 & -(1-F)/L \\ (1-F)/C & -1/(CR) \end{pmatrix}\begin{pmatrix} i \\ u \end{pmatrix}+\begin{pmatrix} U_d \\ 0 \end{pmatrix} \tag{2}$$

$$\dot{X}=AX+B \tag{3}$$

where $x=\begin{pmatrix} i \\ u \end{pmatrix}$, $A=\begin{pmatrix} 0 & -(1-F)/L \\ (1-F)/C & -1/(CR) \end{pmatrix}$ и $B=\begin{pmatrix} U_d \\ 0 \end{pmatrix}$.

The Cauchy formula is used to determine the vector of state variables x:

$$x = e^{A(t-t_0)}x_0 + e^{At}\int_{t_0}^{t} e^{-A\tau}Bd\tau .$$

In the numerical solution, the simulation time is divided into small steps, i.e. $t_{k+1} = t_k + h$.

Then the values of the state variables at these instants of time x_k are calculated (approximately) by the formula:

$$X_{k+1} \approx e^{A_k h}X_k + B\,h \tag{4}$$

where A_k are the values of A currently t_k. For sufficiently small steps h (for example, of the order of T/50), formula (4) works very quickly and reliably.
The MATLAB code with which they are calculated is:

```
Ud=20; L=150e-6; C=10e-6; R=10; f=100000; D=50;
T=1/f, B=[Ud/L;0];
h=T/100; tt=0:h:0.3e-2; n=length(tt); x=[0;0]; xx(1:2,1)=x;
for k=2:n
    contr=1;
    if rem(tt(k),T)<0.7*T, contr=0; end
    A=[0, -contr/L; contr/C, -1/(C*R)];
    Amat=expm(A*h);
    x=Amat*x+h*B;
    xx(1:2,k)=x;
end
```

An additional advantage of this model is that there is no need to model the transistor's drive pulse generation system since the duty factor D can be fed directly to this model. This is standardly referred to as averaged model operation. This reduces the simulation time. In addition, the system for generating the control effect will need to generate a suitable D that varies smoothly, not with a jump like the transistor control pulses.

The control system will be implemented in the Simulink/MATLAB environment, which requires the given code to be embedded in this environment. This is done using the 'MATLAB-function' as shown in Fig.2.

The code in the 'MATLAB-function' block of Fig.2 is;

```
function [iL1,uC1] = fcn(iL,DutyCycle,Time,Step,uC)
Ud=20; L=150e-6; C=10e-6; R=10; f=100000; T=1/f;

D=DutyCycle; tt=Time; h=Step;

x=[iL;uC];
contr=1;if rem(tt,T)<D*T, contr=0; end
A=[0, -contr/L; contr/C, -1/(C*R)];
Amat=expm(A*h);
B=[Ud/L;0];
y=Amat*x+h*B;
iL1=y(1,1);
uC1=y(2,1);
```

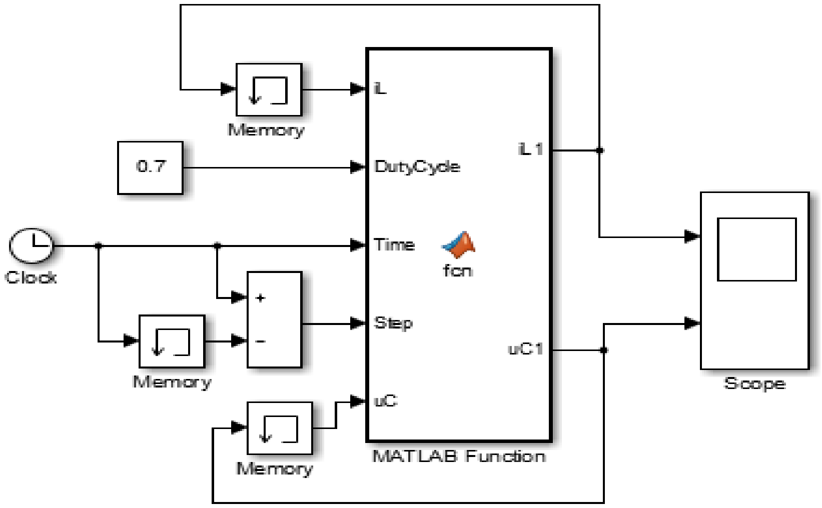


Figure 2. MATLAB/ Simulink model of a step-up DC-DC converter implemented with 'MATLAB-function.

3. SYNTHESIZING A NEURAL MODEL REFERENCE CONTROLLER IN A MATLAB/SIMULINK ENVIRONMENT

The control strategy for the Model Reference Controller is shown in Figure 3. In this architecture there are two neural models, which are realized with two neural networks: a Neural Controller and a Neural Network Plant Model.

The training of neural networks takes place in two stages. First, the neural model is identified (Model Error is minimized for this purpose) and then the neural controller is trained, so that the output of the plant follows the output of the reference model (for this purpose, the Control Error is minimized).

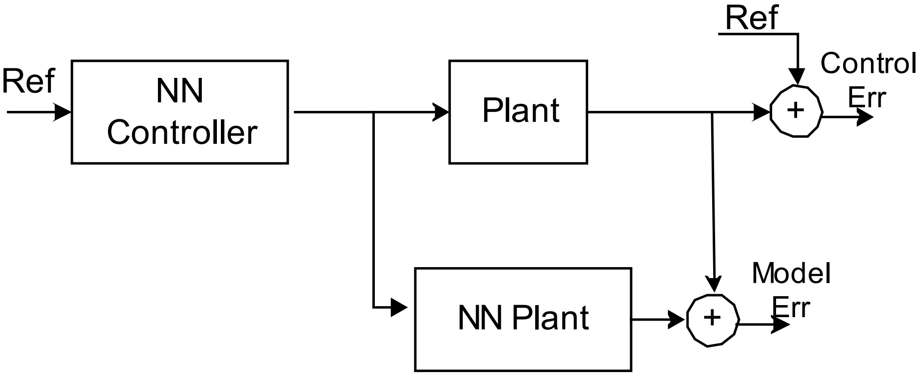


Figure 3. Strategy of the Model Reference Control

The basic structure of the closed voltage feedback system is shown in Figure 4. This scheme includes a buck-boost converter model and Neural Model Reference Controller (MRNC).

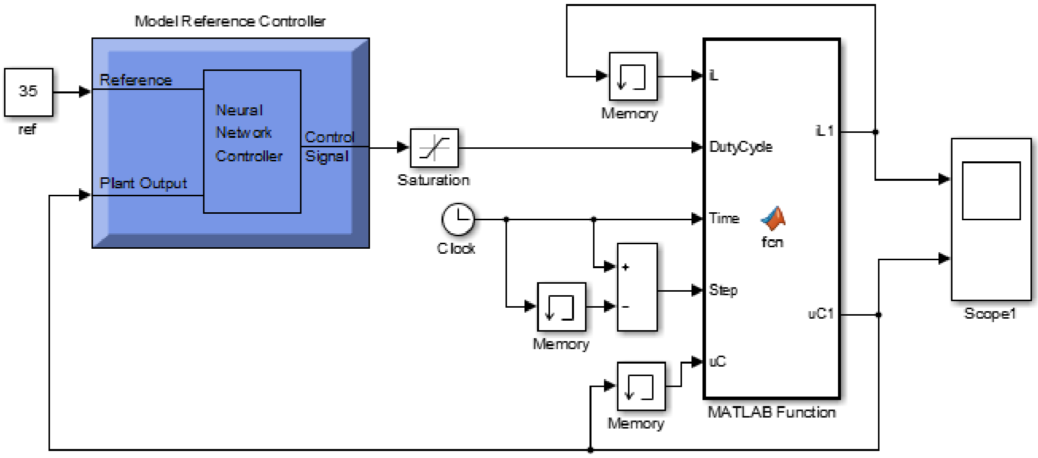


Figure 4. Structure of the close control system

Following are the main steps of the Neural Model Reference Controller based controller training.

First, the structure of the network is selected, after which it is adequately trained. The training uses the open system shown in Fig.5 and stored in the file 'boost_MRC_open'.

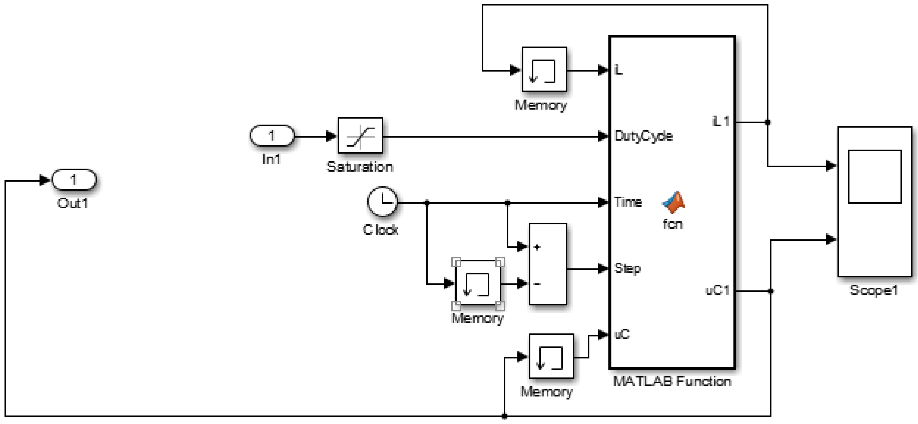
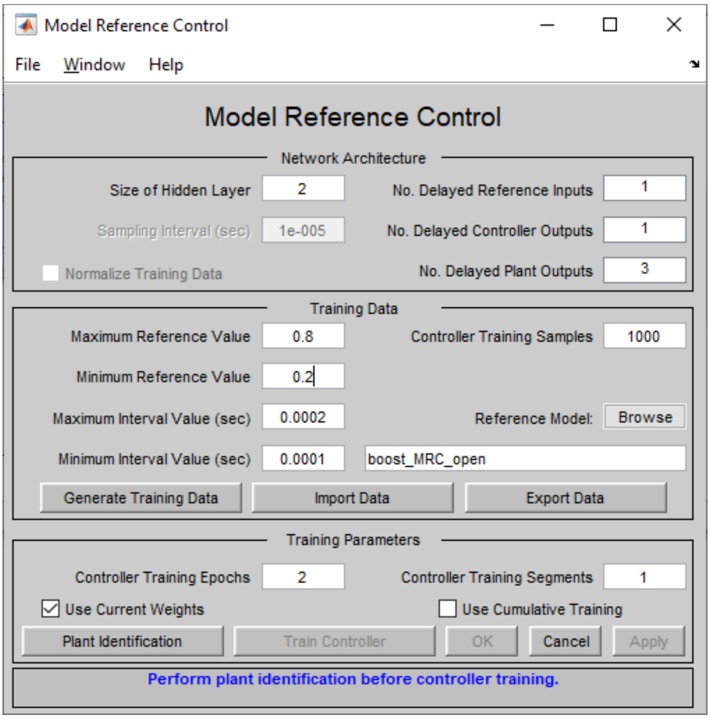


Figure 5. Structure of the open control system

The windows with the parameters for setting and training of the neural networks plant and controller are presented in Figures 6 and 7. The parameters in these windows correspond to the simulation time 0.001 s and the switching frequency f=100000 Hz.



Model Reference Control

Network Architecture

Size of Hidden Layer: 2
No. Delayed Reference Inputs: 1
Sampling Interval (sec): 1e-005
No. Delayed Controller Outputs: 1
☐ Normalize Training Data
No. Delayed Plant Outputs: 3

Training Data

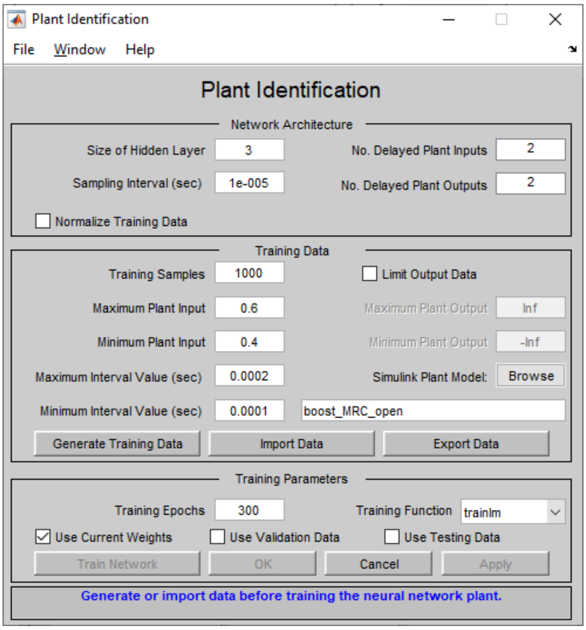
Maximum Reference Value: 0.8
Controller Training Samples: 1000
Minimum Reference Value: 0.2
Maximum Interval Value (sec): 0.0002
Reference Model: boost_MRC_open
Minimum Interval Value (sec): 0.0001

Training Parameters

Controller Training Epochs: 2
Controller Training Segments: 1
☑ Use Current Weights
☐ Use Cumulative Training

Perform plant identification before controller training.

Figure 6. Neural network controller training parameters



Plant Identification

Network Architecture

Size of Hidden Layer: 3
No. Delayed Plant Inputs: 2
Sampling Interval (sec): 1e-005
No. Delayed Plant Outputs: 2
☐ Normalize Training Data

Training Data

Training Samples: 1000
☐ Limit Output Data
Maximum Plant Input: 0.6
Maximum Plant Output: Inf
Minimum Plant Input: 0.4
Minimum Plant Output: -Inf
Maximum Interval Value (sec): 0.0002
Simulink Plant Model: boost_MRC_open
Minimum Interval Value (sec): 0.0001

Training Parameters

Training Epochs: 300
Training Function: trainlm
☑ Use Current Weights
☐ Use Validation Data
☐ Use Testing Data

Generate or import data before training the neural network plant.

Figure 7. Neural network plant identification parameters

In the process of training and identification, the training and identification data of the neural plant and the neural controller shown in Figures 8 and 9 are successively generated.

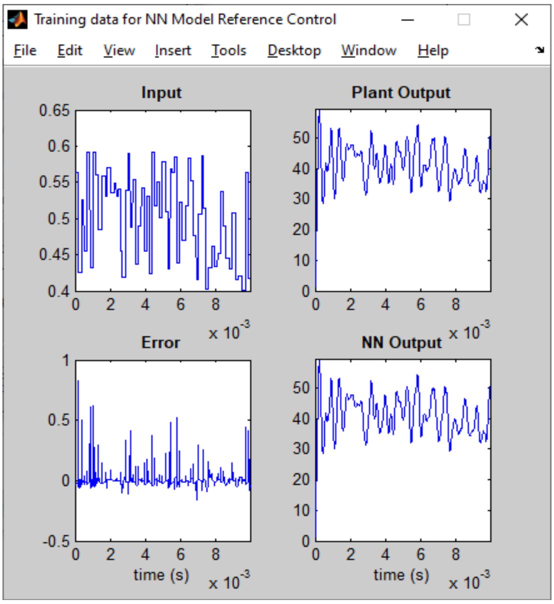


Figure 8. Training data and results of the neural network plant

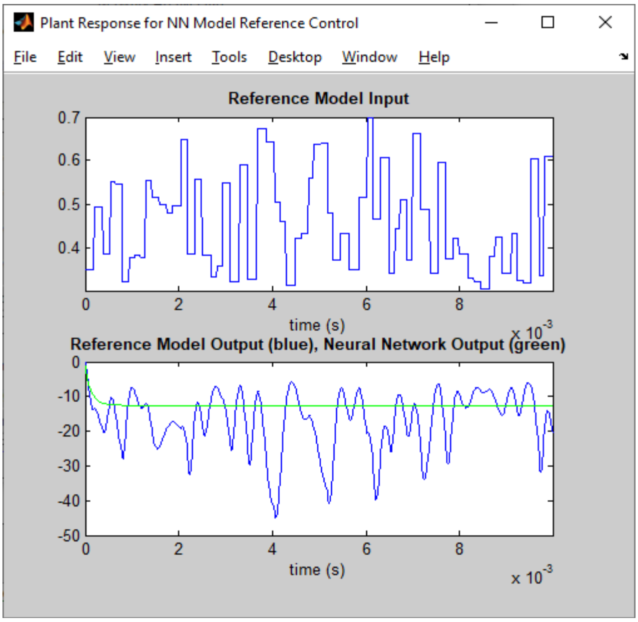


Figure 9. Training results of the neural network controller

After training the controller the operation of the closed system from Figure 4 is simulated. Result is shown on Figure 10.

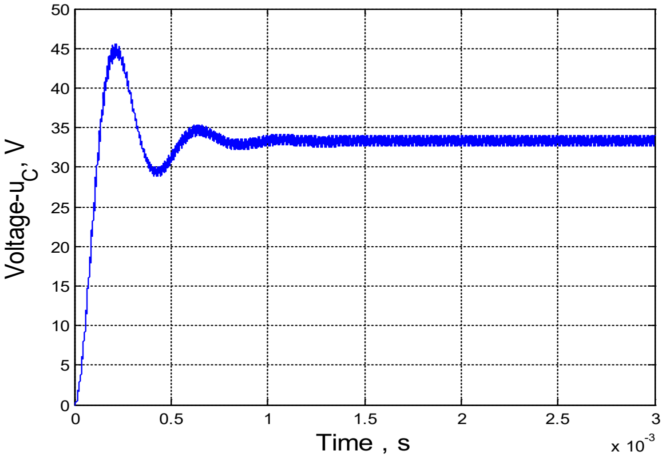


Figure 10. Output voltage of the converter realized with MRNC controller.

4. SYNTHESIZING FUZZY CONTROLLER IN MATLAB/SIMULINK ENVIRONMENT

The closed system used to control the output voltage as well as to synthesize a fuzzy controller is shown in figure 11. It includes, in addition to the inverter model and the system for generating the control pulses, a feedback loop and a fuzzy controller.

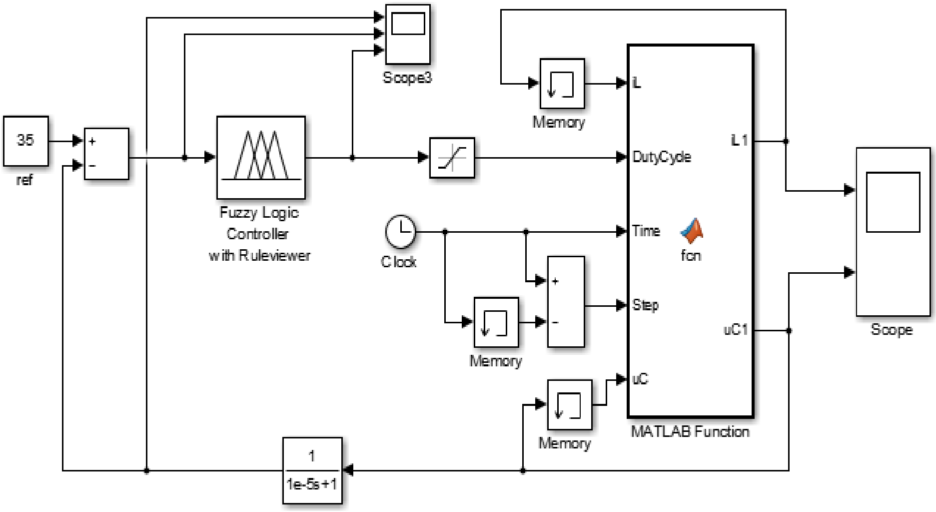


Figure 11. Closed system with fuzzy controller.

All elements of the fuzzy controller setup are given in a FIS file that the Fuzzy Logic Controller block calls. The contents of the FIS file are:

```
[System]
Name='fis'
Type='mamdani'
Version=2.0
NumInputs=1
NumOutputs=1
NumRules=3
AndMethod='min'
OrMethod='max'
ImpMethod='min'
AggMethod='max'
DefuzzMethod='centroid'
 [Input1]
Name='Err'
Range=[-20 40]
NumMFs=3
MF1='1':'trimf',[-20 -5 10]
MF2='2':'trimf',[-5 10 25]
MF3='3':'trimf',[10 25 40]
 [Output1]
Name='Duty cycle'
Range=[0 1]
NumMFs=3
MF1='1':'trimf',[0 0.2 0.4]
MF2='2':'trimf',[0.2 0.4 0.6]
MF3='3':'trimf',[0.4 0.6 0.8]
 [Rules]
1, 1 (1) : 1
2, 2 (1) : 1
3, 3 (1) : 1
```

There are several sections in a FIS file.

In the "Input1" section, the name of the input "Err" is given and the saturation with lower limit -20 and upper limit +40 is defined. Three triangular membership functions are selected, and their parameters are set.

In the "Output1" section, the name of the output "DutyCycle" is given and saturation with lower limit 0 and upper limit 1 is defined. Three triangular membership functions are selected, and their parameters are set.

The rules of the used fuzzy logic are given in the "Rules" section. The rules are chosen so that when “Err” grows, “DutyCycle” grows and vice versa.

Finally, a time is selected to refresh the data of the controller 1e-5.

With the fuzzy controller thus configured, the result shown in figure 12 was simulated.

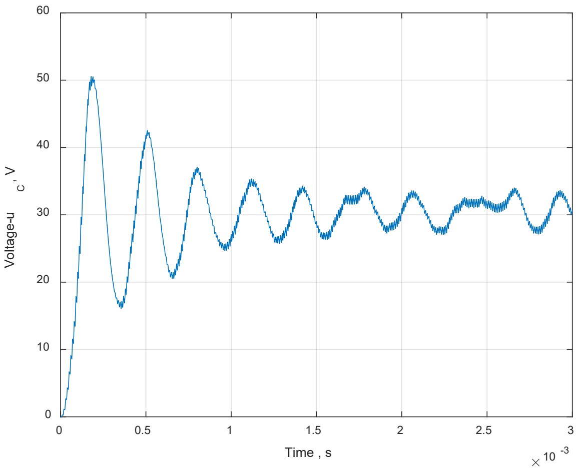


Figure 12. Output voltage of the converter realized with fuzzy controller

5. CONCLUSION

The paper presents a rational approach for the synthesis of control of DC-DC converters, based on the use of Matlab. Specific examples are given for setting up three types of controllers: classic PID, neural network and fuzzy logic. The obtained results are implemented according to known procedures in various types of microcontrollers [8]. Using MATLAB for control synthesis offers significant advantages that make it a popular choice among engineers and researchers in the field of automatic control. He provides an extensive set of modeling and simulation tools. This allows engineers to create complex models of control systems and perform simulations to analyze system behavior under various conditions. MATLAB offers a wide variety of built-in functions and blocks that facilitate the development of control systems. He allows users to write their own functions and scripts, which provides the ability to customize and extend functionality according to specific project needs. In addition, MATLAB easily integrates with other software applications and hardware, including automatic code generation tools, allowing engineers to implement control algorithms. He offers powerful visualization tools that enable easy data presentation and analysis. MATLAB is used by a wide community of scientists and engineers around the world, which means there are extensive learning resources, support forums, and ready-to-use code that can help solve specific problems.

ACKNOWLEDGEMENT

The carried-out research is realized in the frames of the project “Artificial intelligence-based techniques to modeling and designing power electronic devices”, № 232ПД0012-03, Scientific Research Sector of Technical University of Sofia.

REFERENCES

[1] Buso, S., & Mattavelli, P. *Digital control in power electronics*. Morgan & Claypool Publishers, 2015.

[2] A. A. Khristolyubov, T. S. Sekushenko, S. V. Luft, A. I. Khristolyubova and D. V. Makarov. Synthesis of the control system for DC-DC converters for aircraft. *2015 16th International Conference of Young Specialists on Micro/Nanotechnologies and Electron Devices*, Erlagol, Russia, 2015, pp. 547-552, doi: 10.1109/EDM.2015.7184602.

[3] I. O. Bessonov, S. A. Kharitonov, D. V. Makarov and M. A. Zharkov. Synthesis of circuit of regulation of current for buck DC-DC converter. Methodical aspect. *2015 16th International Conference of Young Specialists on Micro/Nanotechnologies and Electron Devices*, Erlagol, Russia, 2015, pp. 391-396, doi: 10.1109/EDM.2015.7184570

[4] C. Vlad, P. Rodriguez-Ayerbe, E. Godoy and P. Lefranc. Explicit model predictive control of buck converter. *2012 15th International Power Electronics and Motion Control Conference (EPE/PEMC)*, Novi Sad, Serbia, 2012, pp. DS1e.4-1-DS1e.4-6, doi: 10.1109/EPEPEMC.2012.6397240.

[5] T. Laszlo, C. Géza and S. Iuliu. Practical synthesis of various control methods for digitally adjusted DC-DC converters. *2014 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM)*, Bran, Romania, 2014, pp. 519-525, doi: 10.1109/OPTIM.2014.6850955

[6] F. Mesquine and H. Khallouk. Robust control of a DC-DC buck converter," *2017 18th International Conference on Sciences and Techniques of Automatic Control and Computer Engineering (STA)*, Monastir, Tunisia, 2017, pp. 432-437, doi: 10.1109/STA.2017.8314873.

[7] N. T. Hien, L. B. Phuong, V. E. Bolnokin. A special mathematical model for the study of electrical circuits components by the method of differential inclusions. *International Journal on Information Technologies and Securit*y, vol.15, no.1, 2023, pp. 69-76. https://doi.org/10.59035/GIRQ4188

[8] Valentin Atanasov, Aneliya Ivanova. A framework for evaluation of web-based learning content. *International Journal on Information Technologies and Security*, vol.14 , no.4, 2022, pp. 13-22.

Information about the authors:

Bogdan Nikolov Gilev – Associated Professor in Department of mathematical modeling and numerical methods, Faculty of Applied Mathematics and Informatics, Technical University of Sofia, Sofia, Bulgaria. Current research interests: mathematical and software models, optimal design, innovation method of control of electric devices.

Nikolay Lyuboslavov Hinov – Associated Professor in Department of Power Electronics, Technical University of Sofia, Bulgaria. Current research interests: development and design of power electronic converters with application in industrial technologies, electric vehicles, decentralized generation of electricity and energy storage.

Kiril Genchev Genev – PhD student in Department of Power Electronics, Faculty of Electronic Engineering and Technologies, Technical University of Sofia, Bulgaria, Current research interests: statistical and information modeling, artificial intelligence, scientifical computing.

Manuscript received on 02 January 2024