Ingeniería Energética,
2024, 45(2): e2410, mayo-agosto,
ISSN 1815-5901

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Technological innovation article

Simulation of direct current converters using Python to improve electronics learning

Simulación de convertidores de corriente directa mediante Python para mejorar el aprendizaje de la electrónica

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Received: January 28, 2024 Approved: April 5, 2024

ABSTRACT/ *RESUMEN*
The objective of the article is to propose the educational application on DC – DC converters based on the free software Python, which allows the analysis, experimentation, demonstration and design of the functions of DC – DC converters. Among the results is the development of five design modules such as Buck, boost, buck-boost, cuk and flyback converters. Among its practical benefits are that students are able to independently carry out their own experiments and designs in a safe environment and contribute to the national development of free computer applications. This type of software is generally privately licensed, with a high acquisition cost, so its counterparts, in free license, allow a greater reach among students and specialists. For the processing and analysis of the information collected, the calculation of absolute and relative frequencies was used as a statistical method.
Keywords: DC – DC converters, free software, teaching-learning process, Python, power electronics.

El objetivo del artículo es proponer una aplicación educativa sobre convertidores CD – CD basada en el software libre Python, que permite el análisis, la experimentación, demostración y diseño de las funciones de los convertidores CD - CD. Dentro de los resultados se encuentra el desarrollo de cinco módulos de diseño como son el convertidor reductor, elevador, reductor – elevador, cuk y flyback. Entre sus utilidades prácticas se encuentran que los estudiantes sean capaces de realizar independientemente sus propios experimentos y diseños en un ambiente seguro y contribuir al desarrollo nacional de aplicaciones informáticas libres. Este tipo de software es generalmente de licencia privada, con un alto costo de adquisición, por lo que sus semejantes, en licencia libre, permiten un mayor alcance entre los estudiantes y especialistas a fines. Para el procesamiento y análisis de la información recopilada se utilizó como métodoestadístico el cálculo de las frecuencias absolutas y relativas.
Palabras clave: *Convertidores de CD - CD, software libre, proceso de enseñanza – aprendizaje, Python, electrónica de potencia.*

INTRODUCTION
Most of the control and measurement system of industrial processes is carried out through electronic circuits, with direct current to direct current converters being a basic module of said control circuits. A direct current to direct current converter, also known as a DC-DC converter, is a type of device that transforms direct current from one voltage level to another. These converters are used in a wide variety of applications, from small computer power supplies to industrial applications to control high power levels, such as solar energy systems, telecommunications, computing, consumer electronics, electric vehicles, industrial control and renewable energy sources [1].

Switched DC-DC converters are devices that perform power conversion by temporarily storing the input power and then delivering it to the output at a different voltage. This can be achieved using inductors which are magnetic field storage devices or capacitors which are electric field storage devices [2,3]. Now, most DC-DC converter configurations are designed to transfer power in a single direction, from input to output, but all switched regulator topologies can be made bidirectional to allow power transfer in either direction. Power semiconductor devices, such as diodes and transistors, are used to perform switching. To achieve effective active rectification, simply replace all diodes in the converter configuration with independently controlled transistors that already have free path diodes included. Converters are available as integrated circuits requiring few additional components, as well as in the form of complete hybrid circuit modules, ready for use within an electronic system.

On the other hand, in consultation with the work of various national and international authors who have developed their research in the use of DC – DC converters both in the field of medicine through the use of diagnostic and monitoring equipment , such as in the field of engineering with dissimilar applications, for example, renewable energy source systems such as solar and wind energy, in power supplies for servers and network equipment, embedded systems and computers, as well as measurement and control in industrial systems. However, the need to continue the development of research regarding the design of DC – DC converters is valued, especially in the improvement of applications that allow the analysis, design and simulation of the different topologies used before their subsequent physical implementation. which enhances the effectiveness of the models to be developed with the consequent reduction in costs, in addition to providing a tool based on free software, like the one proposed here, in which theoretical-practical work can be carried out that enriches and improves the teaching of electrical engineering and therefore the work of engineers in industries [4 - 10].

In any case, knowing the specific characteristics of the DC - DC converter that is used is necessary to verify that its behavior is valid and in turn estimate if it can be used in the application that is being developed or should be replaced by another.The usual way of analyzing a certain circuit that bases its control on the application of a DC – DC converter, starts from initially considering an ideal behavior, and then, based on this study, the limitations introduced by the different real characteristics are analyzed, converter specific. The result of this analysis is either the validation of the DC– DC converter, or the proposal of its replacement by another type of converter with more appropriate characteristics. In this sense, references [11- 14] explain that a critical point in the industry of these devices is the delay periods in their manufacturing. To improve these times, several techniques are available, one of which is the development of new, higher precision models that are capable of reproducing the behavior of the device in various operating conditions and that can be easily implemented in simulators. In this way, its behavior can be predicted before manufacturing, saving time and money.

A problem that university education currently faces is the growing complexity in the field of electrical engineering, especially the study of power converters, which have new topologies and more developed control systems. At the beginning of the development of electronics, teaching was focused on learning each electronic component, its construction, operating principle and typical use cases. Very few tools outside the specialty were required. This has been rapidly changing to modern control specialties, digital signal processing, specialized modeling and simulation software, among many other elements. The limitation of resources for the acquisition of specialized commercial software, which dominates the field of technological research and development, has required the search for competitive alternatives well supported by the community. Correspondingly, taking as reference the studies developed by [15 - 18], the use of free software allows visualizing, building and carrying out interactive simulations of electrical circuits through a graphical interface.

In this way it is possible to learn how electrical circuits work, what parameters to take into account for the design of a certain control circuit and how changes in the different elements affect it. All this helps to improve the teaching-learning process by contrasting the theoretical knowledge studied with the practical knowledge through the simulation method. Simulation saves time in the implementation stage since the result can be observed in the tools before physically implementing it.In that sense, Python is a general-purpose programming language that is characterized by being powerful and easy to learn. It has efficient high-level data structures and an object-oriented programming system. Its elegant syntax and dynamic typing, along with its interpreted nature, make it an ideal language for scripting and rapid application development in various areas and for most platforms.

It stands out for its basic English like syntax, which makes the code easier to read and understand. Additionally, it has a large standard library that contains reusable codes for almost any task. It is open source and free to download. Python has established itself in both academic circles and commercial applications, and its user community is very active. In the scientific field, Python is used for data analysis, simulation and modeling, and has numerous specialized libraries for these tasks. Ngspice is an open source mixed-level/mixed-signal electronic circuit simulator, which is the successor to the latest stable version of Berkeley SPICE.

It is widely used to simulate electronic circuits and is known for its efficiency and industry-specific toolset for electrical design. Ngspice is based on three open-source software packages: Spice3f5, Cider1b1 and Xspice, making it a powerful and popular tool for circuit simulation.It is actively maintained and developed by a community of international users and developers. Overall, Ngspice is a valuable tool for engineers, especially in the field of electrical engineering, for simulation and analysis of electronic circuits. Its "spice" circuit description language is widely used by electronic component manufacturers, as well as in many free and commercial software.

The combination of Ngspice and Python applied to DC – DC converters allows researchers and students to address complex and relevant problems in the field of electrical engineering, improving the efficiency and accuracy of simulation and analysis of electronic circuits. Consequently, the general objective of this work is to propose the free educational application on DC – DC converters, in version 0.5, based on the free software Python, which allows the analysis, experimentation, demonstration and design of the functions of DC - DC converters. This work seeks to solve the problem of increasing the complexity of the study of DC – DC converters by applying the Python and Ngspice programming language as a modeling and simulation tool, which have the support of the international community for the educational and scientific application.

The fundamental scientific contributions made in this work are:

- Development of a generalized structure to model and simulate DC - DC converters, which is used in the university educational field.
- Methodological proposal on how to model CD-CD converters using the Python language.

It should be noted that commercial closed source software is traditionally used to work in the Power Electronics discipline to carry out modeling of complex systems. In this first version, the application consists of the implementation of five modules duly selected in correspondence with the most used functions of DC – DC converters based on the bibliography consulted. The text of the article was organized in order to initially present in a general way the current situation of the topic addressed, in order to expose the need for the development of computational tools through the use of free software, inserting the reader into the current context, in which refers to the knowledge of the development of electronics, taking it to the point of analysis of the practical usefulness of the proposed application.

MATERIALS AND METHODS

In order to develop the objective of this research, it was necessary to verify the existing theoretical studies and search for the scientific knowledge accumulated around the analysis of the models of the most used configurations of DC – DC converters for their implementation in Python for version 0.5.A total of 19 bibliographic references were consulted, in addition to catalogs and technical standards, which allowed continuity to the studies developed by the references [15 - 19] that began in the current context characterized by the turbulent health situation of the pandemic caused by COVID-19, all of which has made it easier to minimize the negative impact imposed by social isolation and the technological costs associated with it to favor the teaching-learning process of the subjects Electrical Circuits and Electronics without need for presence in laboratories.

As an empirical level method, the structured interview was applied to know the students' opinions about the usefulness of the graphical interface application derived from the Python software to improve the teaching-learning process of the Power Electronics subject. The population was made up of 53 third-year students of the Electrical Engineering degree at the "José Antonio Echeverria" Technological University of Havana, CUJAE, in the period 2023, representing 91% of the enrolled students. As a statistical method, the calculation of absolute and relative frequencies was used for the processing and analysis of the information obtained in the interviews carried out. On the other hand, it is important to highlight that designing electronic systems with a focus on reliability, robustness and security is crucial in today's complex and dynamic environments. Reliability is an emergent property of system design, and it is essential to consider it from the early design stages.

Reliability risks are not malicious in nature. Safety and reliability require different design considerations, and both must be taken into account throughout the system lifecycle. System reliability means that the system can perform its functions correctly and consistently, even under conditions of stress or failure, while security means that the system can protect its data and resources from unauthorized access, modification, or damage. authorized. Systems based on power electronics are not exempt from these issues mentioned above. Due to the aforementioned, traditional modeling and simulation programs are lagging behind in the current needs of design and creation of essential skills for the commercial and educational sector. It is no longer enough to be able to model several cases; flexibility is required to take the design to new frontiers that were not even remotely questioned before. This is why a package is required that has expansion possibilities, integration with other technologies and network services.

Python covers these needs through its applications in data science, digital data processing, control algorithms, and a wide collection of libraries that cover practically any need. Or you can simply make your own library tailored to your needs.

DISCUSSION AND RESULTS

PYTHON in the power electronics environment

Python is a programming language that can be used in the power electronics environment to automate processes, perform data analysis, control and monitoring in real time, and for the simulation of electrical power systems.Python has been used in the field of electronics in a variety of applications, some examples being the following:

- **Test and measurement automation**: Python is used to control test and measurement equipment, acquire data, perform analysis, and generate reports. Libraries like PyVISA and pySerial are common in these types of applications.
- **Circuit design and simulation**: Python is used in circuit design and simulation through tools such as PySpice, which provides a Python interface to the popular SPICE circuit simulator.
- **Hardware Control:** Python is used to control hardware through interfaces such as GPIO, I2C, SPI, UART, USB, Ethernet, and more. Libraries like RPi.GPIO and pySerial are common in these types of applications.
- **Signal processing and computer vision:** Python is used in signal processing and computer vision through libraries such as NumPy, SciPy, OpenCV, and scikit-image.
- **Internet of Things (IoT):** Python is used in developing applications for devices connected to the Internet through libraries such as MQTT, CoAP, and RESTful.

Python is a versatile language that can be used in a wide range of applications in electronics and engineering.There are different libraries and tools available to work with Python in the scientific and engineering area. Some of the most recognized Python libraries are:

- **Pandas:** This library provides functions for data analysis, cleansing, exploration and manipulation. The name "Pandas" refers to "Panel Data" and "Python Data Analysis".
- **Matplotlib:** It is a popular graphing library for the Python programming language and its numerical mathematics extension NumPy. It provides a wide range of functionality to create static, animated and interactive visualizations. Additionally, Matplotlib can be used to produce publication-quality figures in a variety of hard copy formats and interactive environments on various platforms. It is open source and can be used for free.
- **NumPy:** It is a library for the Python programming language that adds support for arrays and multidimensional arrays, along with a large collection of high-level mathematical functions for operating on these arrays. NumPy is fundamental to scientific computing with Python and provides an N-dimensional array object, sophisticated casting functions, tools for integrating C/C++ and Fortran code, and useful linear algebra, Fourier transform, and random number capabilities.
- **Scipy:**SciPy is an open-source scientific computing library for Python that uses NumPy as a base. Provides additional utility functions for optimization, statistics, signal processing and more. SciPy includes modules for optimization, linear algebra, integration, interpolation, Fourier transform, signal and image processing, solving differential equations, and other tasks common in science and engineering. It is a fundamental library for scientific computing with Python and is widely used in the scientific and engineering community. SciPy is open source and can be used freely.

As for work environments, there are different options, such as IDLE, PyDev, PyCharm, Spyder or Visual Studio.

Proposed methodology to carry out the modeling of DC - DC Converters

The teaching methodology refers to the set of strategies, procedures and actions organized by the teacher to facilitate student learning. It is a key element in the design of didactic programming for oppositions in education. The teaching methodology can be based on different approaches, such as project-based learning, the flipped classroom, cooperative learning, gamification, design thinking, among others. Its function is to establish how students will be taught, taking into account the objectives, contents, competencies, evaluation and available resources. The teaching methodology evolves along with the new needs that arise in the classroom, and allows the development of the different skills of the students. It is essential to motivate students in their learning and to adapt to changes in the educational field.

In this sense, it is stated by [20,21], that active learning supported in the extensive context of information and communications technologies and in the design of new learning spaces with the optimal use of these resources, establishes a necessary indication for achieve the full path of virtual environments in all study modalities, in addition, the control of learning by the student himself must be supported.Correspondingly, a methodology is proposed that promotes the active participation of students, for this we must define the procedure for the development of power converter models. To model DC – DC converters using the Python language, the following proposal can be followed, which includes the following steps:

1) **Analysis of the DC – DC converter:** Understand the operation and characteristics of the DC – DC converter that is going to be modeled. This includes the type of converter (e.g., buck, boost, buck-boost, etc.), its topology, components, modes of operation, equations of state, and electrical parameters.
2) **Data and specifications collection:** Obtain the data and specifications of the converter, including values of voltage, current, inductance, capacitance, switching frequency, duty cycle, efficiency, and any other relevant information.
3) **Mathematical modeling:** Develop a mathematical model of the DC-DC converter using circuit equations and energy conservation laws. This may include the formulation of equations of state, transfer functions, and state space models. In this work we will use “spice” to define the models.
4) **Implementation in Python:** Use Python and its scientific libraries, such as NumPy and Ngspice, to implement the mathematical model of the converter. This may include defining functions to calculate mean value variables, transient response, and other performance metrics.
5) **Validation and verification:** Verify that the model implemented in Python behaves according to the expectations and data of the real converter. This may include comparison of simulation results with experimental measurements, and validation of the model under different operating conditions.

Converter models

Based on the previous analysis, the application was developed for version 0.5, as already mentioned, in the free software Python, which aims to provide a tool that allows, from simulation, experimentation and demonstration of the functions of the DC– DC converters, to improve teaching activities through interactivity and achieve student independence in the creation of their own designs, as well as contribute to the national development of free computer applications.
On the other hand, the application is intended to provide a work tool for industry engineers that allows them to carry out, from simulation, the analysis of the designs of the different applications of the converters in order to obtain the best variant for their implementation. practice.

There are a number of basic DC – DC converters, from which all other more advanced DC – DC converter topologies are derived. Some of the most relevant basic converters are:

- Buck
- Boost
- Buck – Boost
- Cuk
- Flyback

There are several ways to classify DC-DC converters, by the electrical isolation capacity between the input and the output, between the ratio of the input voltage and the output (if the output has a higher voltage than the input, it is called step-up), among other.In this work, as an example, buck, buck-boost and Flyback converters will be modeled.The topology of these converters is shown in figure 1.

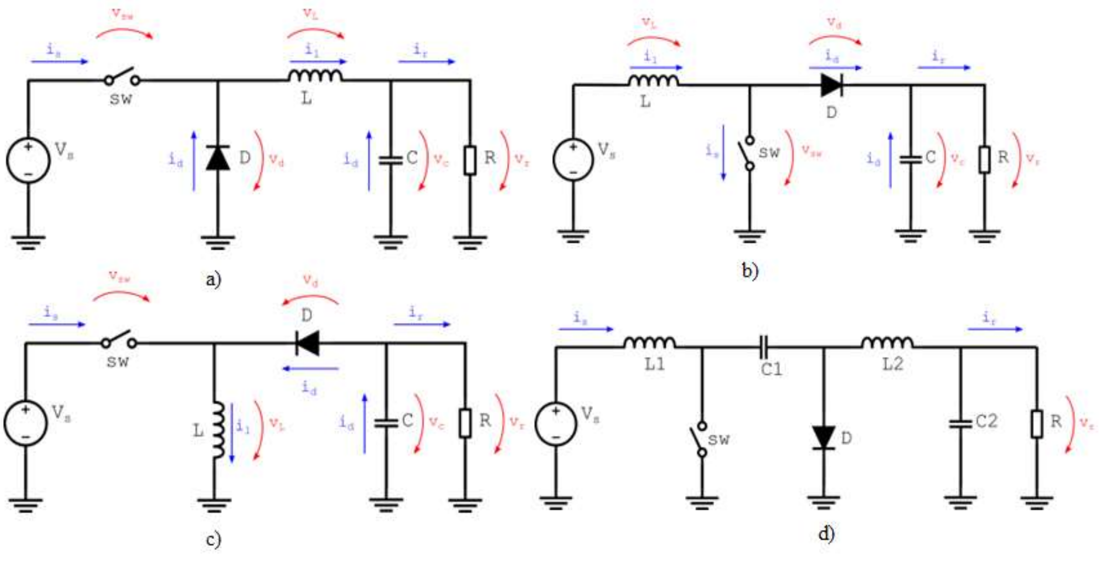

Fig. 1. a) Buck converter topology. **b)** Boost converter topology. **c)** Buck-boost converter topology. **d)** Cuk converter topology. Own elaboration

For Buck converter topology is controlled for switch (transistor) and a diode are used in this circuit, as well as energy storage elements.The relationship of the output voltage (V_R) as a function of the input voltage (V_S) is defined as a function of the useful cycle (D) of the converter by the following equation (1):

$$D = \frac{V_r}{V_s} \qquad (1)$$

The boost converter is constructed by changing the layout of the components of the buck converter. The relationship of the output voltage as a function of the input voltage is defined in this case b) as the function of the useful cycle of the converter by the following equation (2):

$$\frac{1}{(1-D)} = \frac{V_r}{V_s} \qquad (2)$$

As the name indicates, the buck-boost converter can operate in the above two possibilities. The number of elements is maintained, but it operates with a reversal of the polarity of the output voltage. For this case, the relationship between input and output is by the following equation (3):

$$-\frac{D}{(1-D)} = \frac{V_r}{V_s} \qquad (3)$$

The Cuk converter has a greater number of elements in its construction, this being one of the important elements when selecting a topology: its simplicity. Now we have twice as many energy storage elements. Its input and output voltage relationship is characterized by equation (4):

$$-\left(\frac{D}{(1-D)}\right) = \frac{V_r}{V_s} \qquad (4)$$

Finally, the isolated topology of the Flyback converter will be analyzed. This converter is widely used in many homes' electronic applications such as televisions, video players, set-top boxes and many other equipment. In the figure 2, we have the graphic description of the topology.

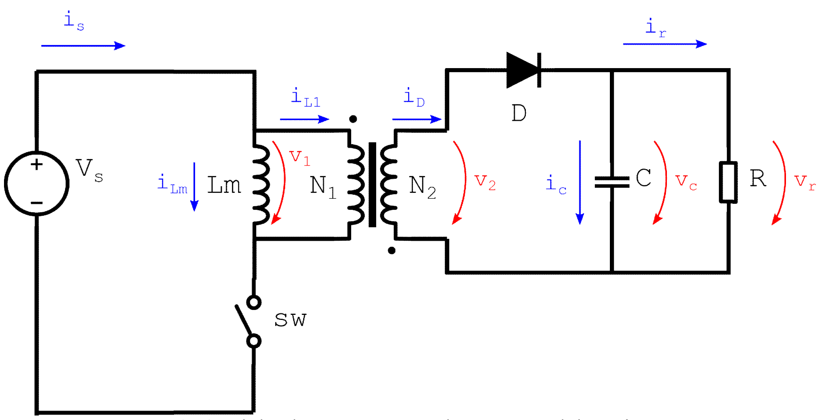

Fig.2. Flyback converter topology. Own elaboration

The transformer that provides isolation and a change in the transformation ratio of the converter is of the type that works at high frequency. For its modeling, a model with concentrated magnetizing inductance in the primary is generally used, with an ideal transformer model to complete the basic topology. In equation (5), the relationship of the voltage between the input, the output and its dependence on the useful cycle and the transformation of the transformer can be observed:

$$V_r = V_s \left(\frac{N_2}{N_1}\right)\left(\frac{D}{1-D}\right) \qquad (5)$$

Due to the presence of the transformer, this converter can be the equivalent of a buck, boost, or buck-boost. In all cases, special attention must be paid to the current that circulates through the inductors. If the current never reaches zero in the stable state of the converter, we are in the presence of "continuous conduction work mode". Otherwise, we are operating the converter in the current discontinuous mode. This has important implications for how the converter is designed or controlled. It even changes the voltage conversion ratios

An interface developed with Python has been created for each converter so that the user can modify the values of the circuit model and obtain numerical and waveform results. Each application consists of three types of windows: the program's graphical interface, a background window, and graphs of the results.The interface of each tool developed is composed of a section for data entry, one for numerical answers, a section for help, a description and finally, the section where the circuit model is displayed.

Buck converter
The program interface is shown in figure 3.

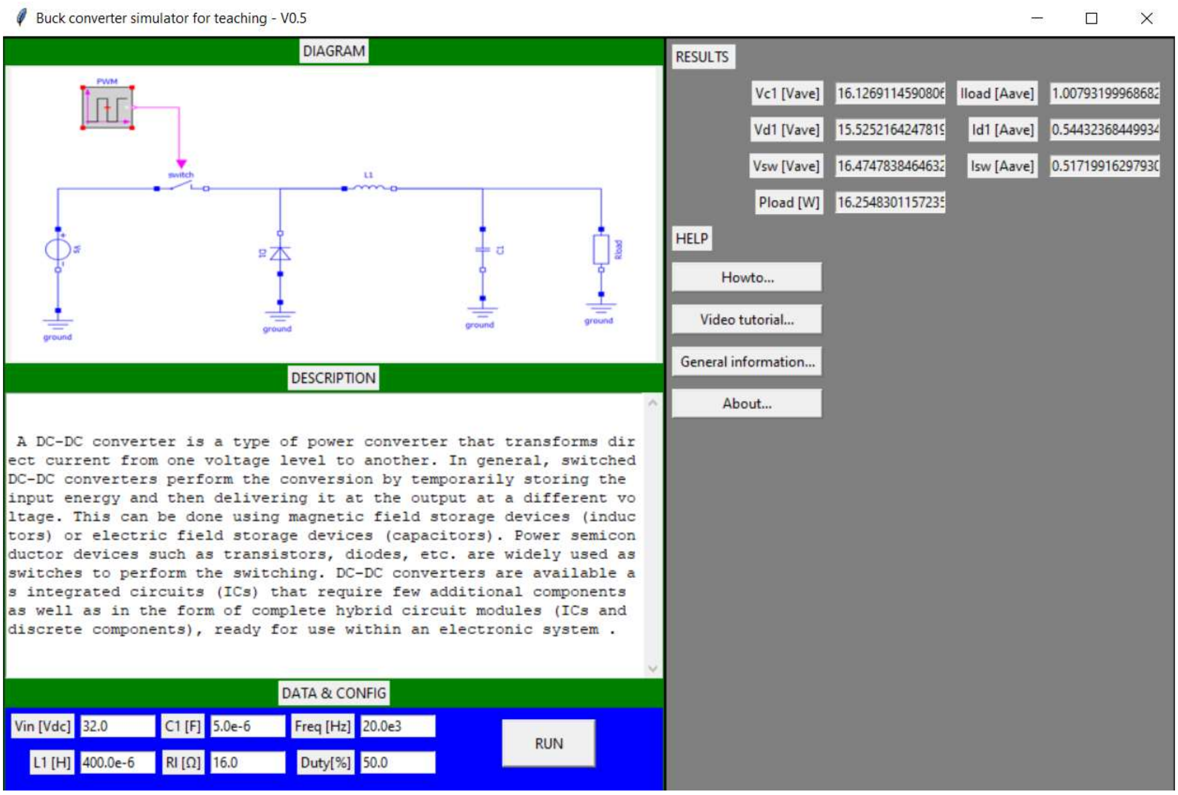

Fig. 3. Buck converter simulation program interface. Own elaboration

The data necessary to model this case are the input source voltage, inductance, capacitance, switching frequency, load and useful cycle of the switched signal. This model is solved using the Ngspice simulation tool, so it can operate in both current modes: continuous or discontinuous. This provides simplification and encourages students to focus on the essentials, more on the mathematics involved for each case. At least in undergraduate stages, it is more important to understand the essence of converters than to focus on the specific mathematical models of each case.A strategy to ensure that the skills developed with this type of tool are practical and lasting is the use of the "spice" language to model electronic components. To do this, every time the application developed in Python is run, the description of the circuit is printed on the console screen in the background. This can be seen in figure 4. In general, all programs have such a console, with the printing of the models, to be reused in other programs or tools.

```
Imprimiendo el circuito:  .title Convertidor Buck
.include C:\Users\jobs\Downloads\PySpice\scripts_pyspice\libraries\mosfet\irf150.lib
.include C:\Users\jobs\Downloads\PySpice\scripts_pyspice\libraries\diode\schottky\1N5822.lib
XS1 n1 g1 n2 IRF150
XD1 n2_a n2 1N5822
Vin n1 n1_a 32.0
Rshunt_vin n1_a 0 1e-05
Rshunt_d1 n2_a 0 1e-05
Rshunt_l1 n2_aa n3 1e-05
Rshunt_c1 n3_a 0 1e-05
L1 n2 n2_aa 0.0004
C1 n3 n3_a 5e-06
Rload n3 0 16.0
Vpulse1 g1 n2 DC 0V PULSE(0.0V 12.0V 0s 0s 0s 2.5e-05s 5e-05s)
```

Fig. 4. Description of the step-down converter model in “spice” language. Own elaboration

Executing the program creates a new graphic window, where we can see the main waveforms of the converter, as can be seen in the following figure 5.

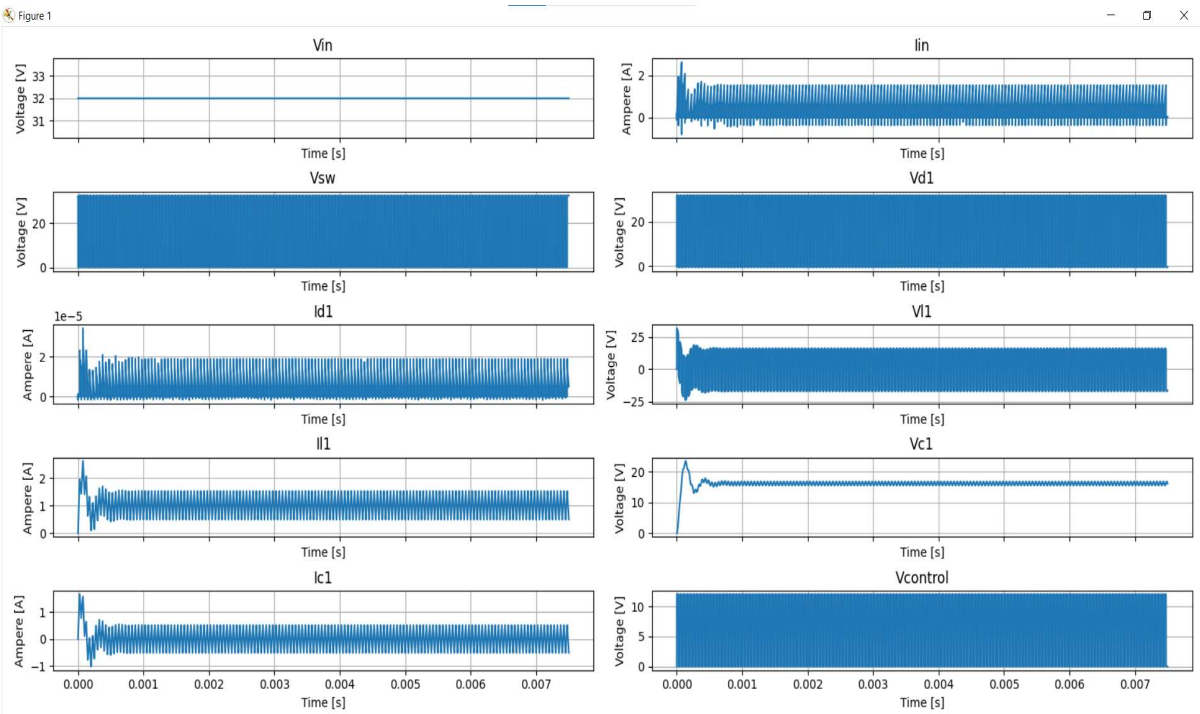

Fig. 5. Capture of the graphical results of the buck converter simulation. Own elaboration

If any of the graphs are zoomed, there is an implementation in the program so that all other graphs are updated at the same time interval. This is of utmost importance in the study of power converters, to be able to observe specific details at relevant time intervals.Unlike traditional explanations in class, this type of simulation allows us to observe, in addition to the stable state, the start-up of the converter and the possible effects on the load or the network during its insertion.

Buck – boost converter

This converter, like the previous one, is explained after detailing the step-down and step-up converters in the students' teaching activities. In figure 6, we can see the tool created for this converter, maintaining a simple and regular interface between all programs.The graphical results are shown in figure 7.One of the most attractive modifications to these converter models is changing the switching frequency, to see how it affects the waveforms as well as the quality of the converter output current.

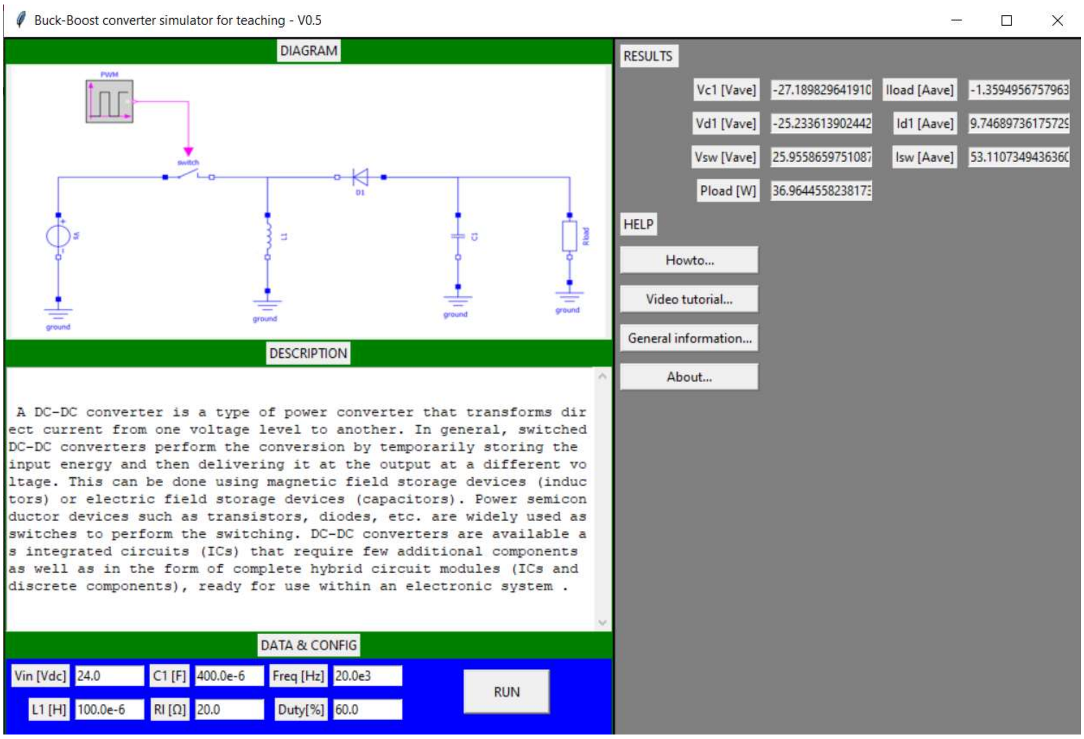

Fig. 6. Description of the buck-boost converter model in "spice" language. Own elaboration

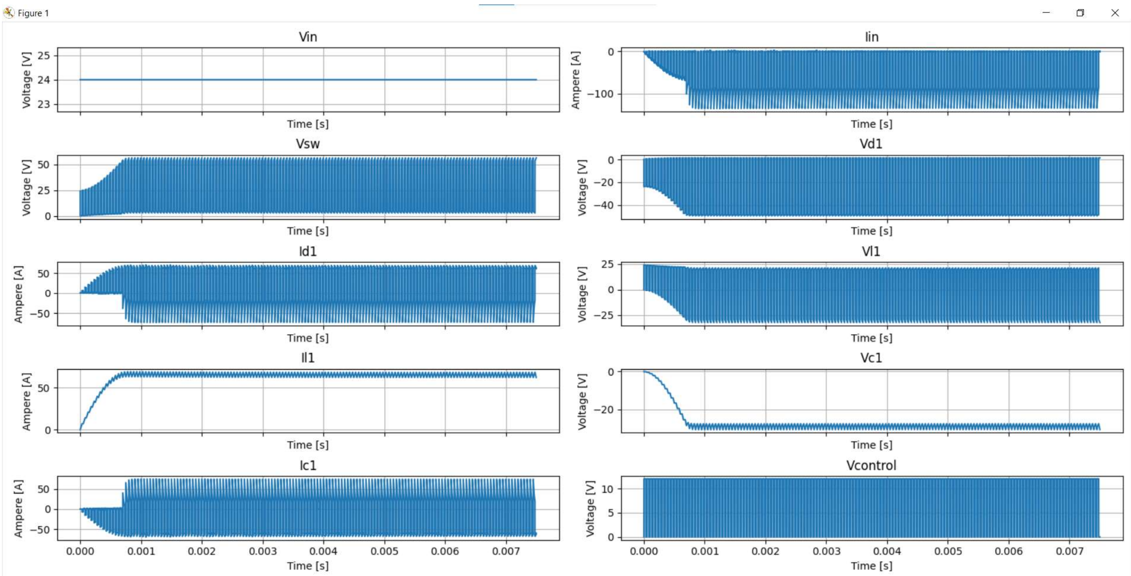

Fig. 7. Capture of the graphical results of the buck-boost converter simulation. Own elaboration

Flyback converter

The Flyback converter is widely used in many commercial and research applications. The use of the transformer as a temporary energy storage element for the transfer and obtaining of the output voltage creates a change in the mentality of students towards power converters of this type. This is fundamentally due to the differences between the low frequency transformers (50 Hz or 60 Hz) of the electrical power systems and the operation of the transformers and inductors in the converters, as energy storage elements. In figure 8, can observe a screenshot showing the interface of the tool for simulating the Flyback converter.

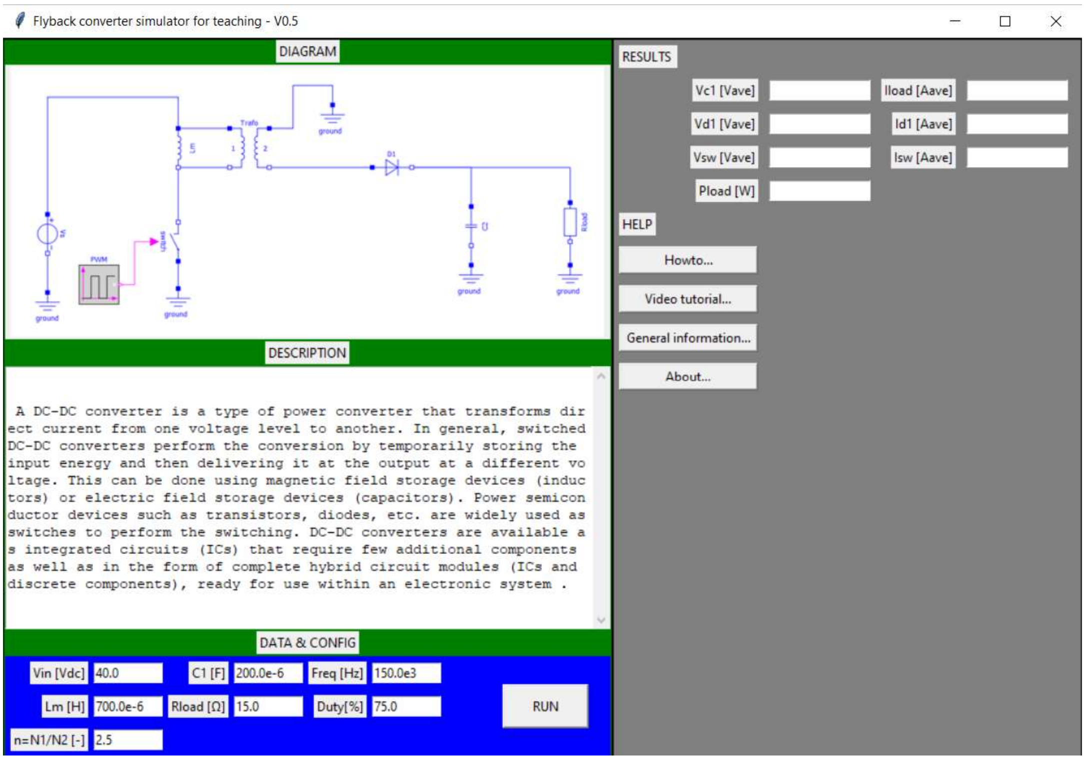

Fig. 8. Screenshot of the program interface for simulation of the Flyback converter model. Own elaboration

This type of converter requires greater effort from students to understand and master its operation. The complexity introduced by the transformer makes it require more simulation cases. In figure 9, we can see a selection of the waveforms of the Flyback converter simulated with the tool.

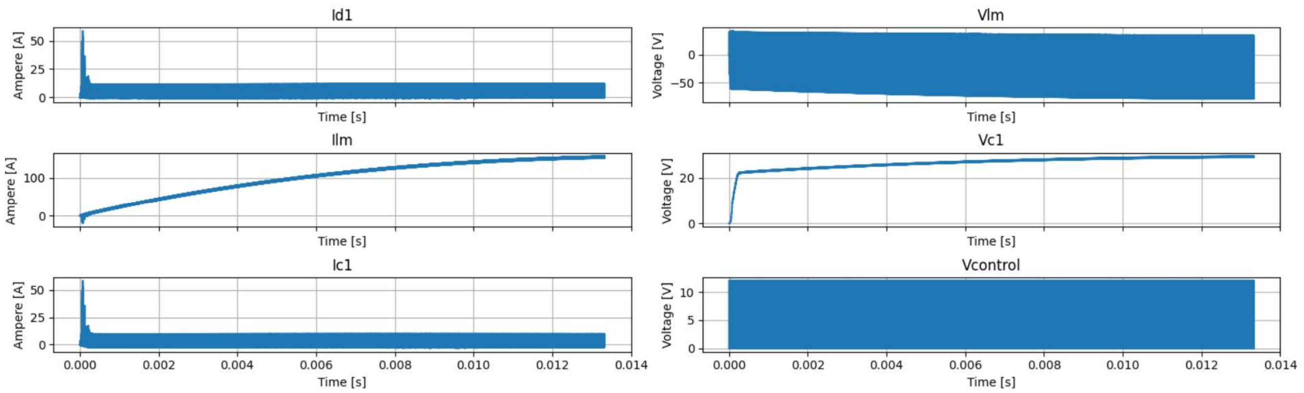

Fig. 9. Capture of a fragment of the simulated waveforms of the Flyback converter. Own elaboration

It is important to be able to observe the waveforms in their most important details, such as the changes of states in the converter elements, with each closing or opening operation of the switched switch (transistor).

ANALYSIS OF THE RESULTS

With the objective of analyzing and evaluating the results obtained with the proposed application were interviewed 53 students of the 3rd year of the electrical engineering degree at the Technological University of Havana, Cujae, that studied the subjects of Power Electronics in the period 2023.The form that served as a guide for conducting the interview was structured as follows:

Question No. 1. Do you consider that the application developed in Python helped to reinforce the theoretical content with the practical content, as well as the development of practical skills?

Question No. 2. Did using the application increase motivation for the race?

The answers to this questions are shown in table 1.

Table 1. Results of Questions

Question No. 1		
	Frequency	%
Yes	53	100
No	-	-
Total	53	100
Question No.2		
Yes	48	90
No	5	10
Total	53	100

Analysis and interpretation:

It is observed that 100% of the students interviewed consider that the application developed with the free software Python helped them reinforce and improve the learning of the theoretical-practical contents taught in the teaching activities, as well as to develop skills in the design of control circuits using DC - DC converters. That is could be interpreted that from the use of the application as an educational tool an improvement has been obtained in the teaching-learning process of the subject of Electronics, specifically on the topic of converters.On the other hand the 90% of the students interviewed state that the use of the application helped them increase motivation for the career because in addition to the theoretical-practical knowledge acquired with the tool, these are also applied to real case studies of the profession such as the design of DC – DC converters in electric vehicles.

CONCLUSIONS

In this work, the combination of Ngspice and Python in the study and development of DC – DC converter applications allows researchers and students to address complex and relevant problems in the field of electrical engineering, improving the efficiency and accuracy of simulation and analysis of electronic circuits. The fundamental scientific contributions of the present work include:

- Development of a generalized structure to model and simulate DC – DC converters, which can be used in the university educational field.
- Proposal of a methodology to address the modeling of DC -DC converters using the Python programming language.

This approach proves to be a valid alternative to closed source commercial software systems for working in the discipline of power electronics, promoting innovation and the development of more precise and efficient models in the teaching and research of electronic circuits.On the other hand, the methodological work developed in the subject of Power Electronics in the Electrical Engineering degree at the Faculty of Electrical Engineering of the Technological University of Havana, Cujae, enhances the development, through experimentation, of educational tools through the use of free software such as Python, which has raised the level of motivation and interest of students in the career with the consequent improvement of the teaching-learning process of electronics.

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CONFLICT OF INTERESTS

The authors declare that there is no an interest conflict.

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