LOAD MODELLING IN ELECTRIC POWER SYSTEMS: COMPUTATIONALLY IMPLEMENTATION OF GRAPHICAL INTERFACE AND QUALITATIVE ANALYSIS

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Abstract. This paper presents a computationally graphical user interface aiming to model electrical loads. The developed tool provides a user-friendly interface for entering the electric power system data in order to obtain the values of electric current, voltage and power absorbed to the load, considering the following load representation models: constant impedance, constant power, and constant current. The user selects one of the models and the tool provides the graphs of the generator voltage, the voltage drop across the line and the load voltage. The correct modelling of electric loads allows planning and operating the electrical systems with better accuracy indices, which reflects directly on economy, reliability, and safety. Currently, the process of modelling the elements of electric power systems has been widely explored by researchers and it has been demanded a greater contribution from utilities and government agencies in order to the sector's de-verticalization, increasing the market competitiveness, operation quality indices and greater consumer awareness. In educational scope, the effectiveness of interdisciplinary projects, such as the development of computational tools which provide greater simplicity in the daily routine of professionals from electric power sector, reflects in greater interest and search for the knowledge by the students, leading to a more successful in the teaching-learning process. Therefore, Matlab software was used for the graphical tool development for electric power systems analyses. The friendly environment for data input and presentation of results provides a greater facility to use the tool and easy interpretation of the results. Within this context, for the analysis of the load representation models influence, simulations were performed considering a test system with different values of power factor. Finally, the results obtained and the software developed demonstrate the feasibility of using the tool to analyze the influence of different models of load representation. Additionally, concerning the educational scope, the development of interdisciplinary projects improves the teaching-learning process.

Keywords: Load modelling, Graphical interface, Electric power systems

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1   Introduction

Electric power systems are constantly evolving. Technical, philosophical restructurings and the inclusion of intelligent equipment in the electricity grids correspond to the current reality of utilities. These new features of the systems require the study and development of innovative tools and concepts to assist the decision making process in the operation and planning stages.

Increased market competitiveness, quality of operation indicators imposed by regulators and greater consumer awareness contribute to the technical, economic, political and environmental improvement of the agents in the electricity sector.

The planning and operation of electric power systems has as its primary objective the supply of energy to its consumers ensuring adequate levels of safety, reliability, continuity, quality and economy, considering the variations in demand and respecting the operating restrictions. Thus, it is essential to employ adequate models for the representation of the system elements, which will allow the analysis of the steady-state electric power systems and the transient responses to obtain reliable results, enabling the implementation of actions defined in the planning studies and decisions arising from the operation of the system, which lead to safety, reliability and rapid return of the investment. Therefore, the modelling process of the electric power systems elements has been widely explored by the researchers and demanded a larger contribution from the utilities and government agencies [1-5].

According to [6], a static load model "expresses the active and reactive powers at any given time as a function of the magnitude of the bus voltage and frequency for the same instant". Loads with static characteristics, such as resistors, incandescent lamps, and equipment such as transformers and reactors, are modeled by algebraic equations, particularly exponential and polynomial equations.

When slight voltage and / or frequency variations occur, the system returns to steady state quickly, in which case it is possible to model the load by static models without loss of generality.

Also, as stated in [6], a dynamic load model "expresses the active and reactive powers at any given time as a function of the magnitude of the bus voltage and frequency at a previous time, and generally in the present instant." Loads that have dynamic characteristics such as motors, discharge lamps and protective relays can be modeled by either algebraic equations or differential equations.

In studies involving the complete safety assessment of electric power systems, load modelling should be done in a complementary manner, so that the static load model is implemented in the power flow studies and the dynamic load model is used for eventual time domain simulations [7].

The authors in [8] formulated the mathematical problem as a linear model relating load measurements with normalized load curves (state variables) for the individual customer groups. The linear model is given by a priori knowledge of the normalized load curves and the fixed load composition at the substation level. In [9] the authors considered the significance of load voltage dynamics in studies of power system damping. A generic model of dynamic loads is used to investigate the influence of active and reactive power dynamics on the damping of oscillations in a multimachine power system. In [10] the researcher examines the effects of different load models upon voltage stability. Both static and dynamic load models are considered. The relationship among the nose point of the curve, the point of system bifurcation, and the stability of different regions of the P-V curve are also examined. It is shown that the load model has a significant effect in the determination of system voltage security.

These relevant publications denote that an accurate load modelling process directly influences the operation and control of electrical power systems. From a primary perspective, in the academic field, in which we seek to build knowledge about the theme together with students through methods in which they become protagonists of the process and the use of technological tools that further arouse interest in the subject. It will be equally relevant, since proper training for future professionals and researchers in the area is appropriate. Within this context, interdisciplinary projects aimed at building knowledge globally, stimulating a new understanding of reality, are fundamental to the teaching and learning process.

Therefore, this paper adopts, within the static load model, three distinct ways of representation to analyze the same test system load: the constant impedance, constant current and constant power models, which are briefly described as follows.

- Constant impedance: power varies quadratically with respect to the change in voltage magnitude;
- Constant current: power varies linearly with respect to voltage, while current modulus and power factor are maintained;
- Constant power: Power does not vary with changes in voltage magnitude.

From this perspective, this work presents a computationally implementation of graphical interface and qualitative analysis related to load modelling in electric power systems. Simulations were performed considering different power factor values.

The remainder of this paper is organized as follows. Section 2 describes the methodology adopted for load modelling and graphical interface development. The test system is shown in Section 3. Section 4 presents the experimental results and discussions. Lastly, the conclusion of this paper is presented in Section 5.

2 Methodology

From the adopted test system, the load modelling was performed based on the impedance, power and constant current models. Figure 1 shows the relationship between the absorbed power and the voltage applied to the load for the three load representation models.
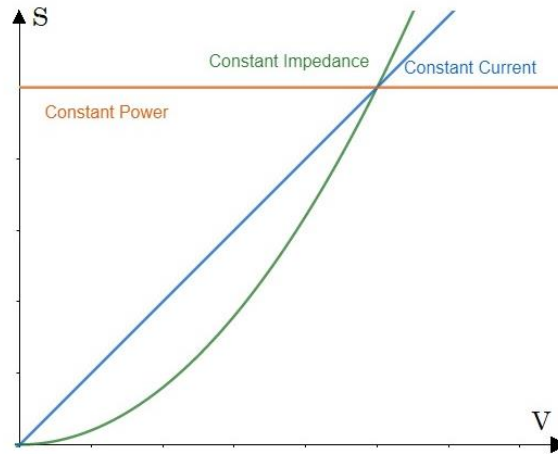

Figure 1. Power absorbed in relation to voltage

The equation used in the programming for each case was obtained in [11] and will be described as follows.

- **Constant impedance**

In this model, the impedance presents a constant value and is represented by $(\bar{Z}_C)$. Its value is obtained from the nominal active (P_{NF}) and nominal reactive (Q_{NF}) powers absorbed by the load considering a nominal value of voltage (V_{NF}) as showed in (1).

$$\bar{Z}_C = \frac{V_{NF}^2}{S_{NF}} \angle \varphi = R + jX, \tag{1}$$

where R is the load resistance, X is the load inductive reactance and $j = \sqrt{-1}$ (imaginary number). The variables subscript NF refers to nominal values per phase.

The power absorbed by load $(\bar{S}_F = P_F + jQ_F)$ is represented in (2) for any value of voltage $(\dot{V}_F = V_F \angle \theta)$.

$$\bar{S}_F = \left(\frac{V_F}{V_{NF}}\right)^2 \bar{S}_{NF},$$

(2)

where $\bar{S}_{NF} = P_{NF} + jQ_{NF}$.

Therefore, the power absorbed by the load varies quadratically with the voltage (V_F), and can also be obtained by the product of the voltage at the load terminals by the current conjugate.

- **Constant current**

In this model, it is considered that the modulus of current and power factor are constants. Its value is obtained from the active (P_{NF}) and reactive (Q_{NF}) powers absorbed by the load considering a nominal value of voltage (V_{NF}) as showed in (3).

$$\dot{I}_{NF} = \frac{S_{NF}}{V_{NF}} \angle \theta - \varphi,$$

(3)

where $\dot{I}_{NF} = I_{NF}\angle\theta - \varphi$. Note that, θ is the voltage angle and φ is power factor angle. These parameters are entered by the user.

Thus, for any value of applied voltage to the load, the current is obtained from (4).

$$\dot{I}_F = I_{NF}\angle\theta_1 - \varphi.$$

(4)

The variation of the current phase angle demonstrates that the system power factor is maintained as well as the current modulus.

The programming of this load model requires an iterative strategy, using, among other, loop repetitions, in order to evaluate the calculation of each iteration. The convergence criterion adopted is the difference between the current voltage and the value obtained from the last iteration. The maximum difference admissible is set by the user.

The absorbed power is calculated as showed in (5).

$$\bar{S}_F = \frac{V_F}{V_{NF}}\bar{S}_{NF}.$$

(5)

Thus, from (5) it is possible to observe that the power absorbed by the load varies linearly with the applied voltage.

- **Constant power**

In this model, the active and reactive power are equal to their nominal single-phase values (P_{NF}) and (Q_{NF}), respectively. Thereby, the current absorbed by the load, considering any value of voltage is presented in (6).

$$\dot{I}_F = \frac{S_{NF}}{V_F}\angle\theta_1 - \varphi,$$

(6)

where $\dot{I}_F = I_F\angle\theta_1 - \varphi$.

From the obtained value of load current (6), the values of drop voltage and load voltage are calculated by an iterative process. Therefore, the obtained values of load voltage are compared at each iteration, until the difference between the current and the last value is less than a minimum established by the user. The obtained values of the last iteration are used to display the values in a table and plot the

results.

Through the Matlab software, it was used the graphical environment for user interaction, specifically the GUIDE (Graphical User Interface Development Environment) aiming to create a graphical interface that presents the phasor diagrams of the generator, line and load. In addition, other information is also presented and will be detailed below. This computational tool was of great importance for the accomplishment of this work, since it provides reliability and agility in obtaining the results, thus allowing the specialists to execute their analysis and decision making with greater precision.

The creation of a graphical interface through the GUIDE environment aims to facilitate the user interaction with the program through graphics. In this paper, the user defines the input variables (generator line voltage, voltage phase difference, line resistance and inductive reactance, active three-phase load power, power factor, and tolerance, used as a stopping criterion in iterative methods). Furthermore, the load model (constant impedance, constant current and constant power) is also selected by the user for analysis.

Thereby, the developed interface is presented in Figure 2. Note that, it is subdivided into three blocks, enumerated from one to three. As follows, it is detailed the function of each block.
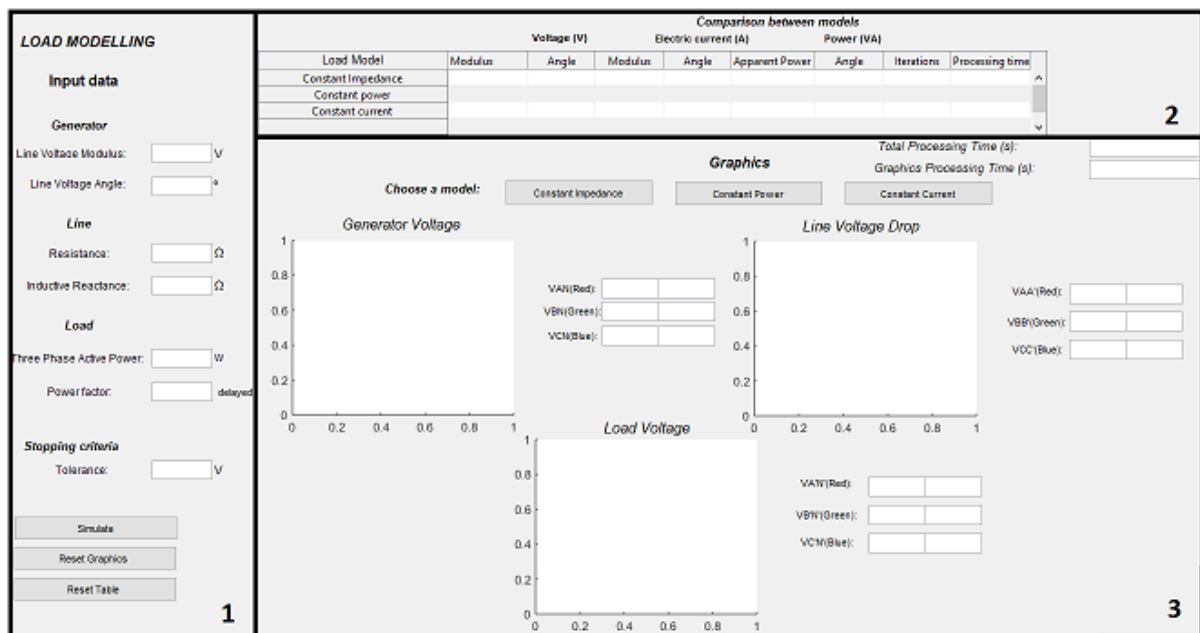

Figure 2. Developed interface

1. Input Data – In this block, the user enters all necessary system data in order to represent the load modelling. More specifically, the generator line voltage and its phase reference, the resistance and inductive reactance of the line, the three-phase active power and power factor. Finally, the desired tolerance that is used as stopping criterion for iterative methods. Additionally, the interface presents three buttons that aim to start the simulation (inserting the calculated data into the table), reset graphics and reset table. The objective of adding these three buttons is to facilitate the simulation of different scenarios.

2. Comparison table among the models of load modelling – In this block, a table shows the value of voltage, absorbed apparent power, load current, number of iterations and processing time for the chosen load representation model.

3. Phasor diagrams related to the chosen load representation model – In this block, the user selects which load representation will be displayed in the plotting area. It is exhibited the voltages of generator, line and load. In order to guarantee a better visualization of results, it is presented text boxes that show the modulus and phase of the voltages.

In addition, to assist in the process of modelling and analysis of results, the program developed by

the authors enables the visualization, in the graphical interface, of phasor diagrams of the generator and load voltages, as well as voltage drop in the system transmission line. Therefore, determining the regulation of the analyzed system becomes easier to obtain by the user.

The developed computational tool makes this project flexible in order to analyze different systems, because the input data is inserted by the user and could be easily changed. In addition, it enables users who have basic knowledge of electrical power systems to use the software without major difficulties. These aforementioned facts highlight the usefulness of the computational tool developed in this work.

3   Test system

The test system employed is symmetrical and balanced, whose circuit is shown in Figure and presents the following nominal data:

- Line voltage at generator output: 380 V
- Line resistance: 0,2 Ω
- Line inductive reactance: 0,4 Ω
  The nominal load parameters values are given by:
- Line Voltage: 380 V
- Three phase power: 27000 W
- $cos\varphi = 0,9$ lag

The maximum voltage variation, adopted as the stopping criterion to the iterative-based methods, is 0.1 V.
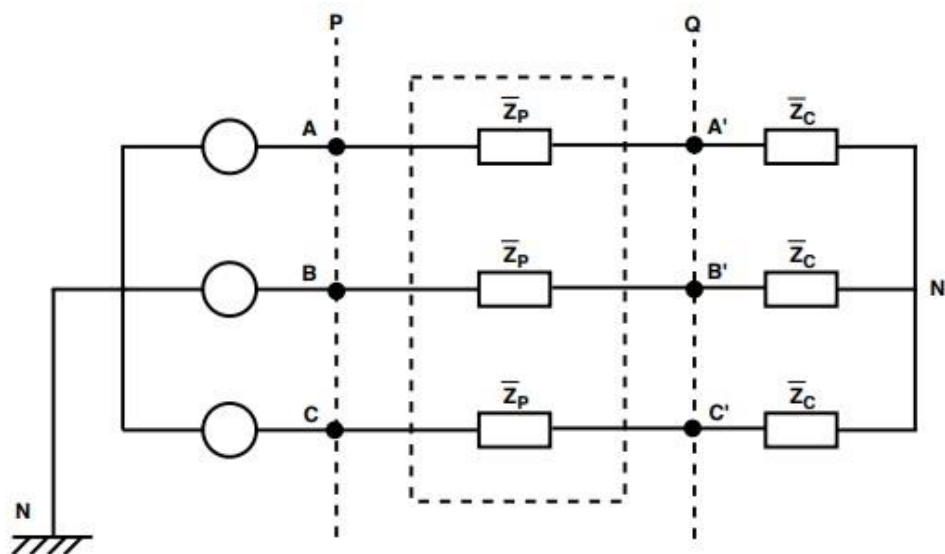

Figure 3. Circuit for comparison of the load representation models

Besides visualizing the numerical results obtained in the simulations and displayed in the interface table, it is possible for the user to analyze the generator voltage, the line voltage drop and load voltage, more simply and quickly using the phasor diagrams provided by program, which will be displayed according to the user-selected model representation in the interface.

4   Results

The test system simulations, for the three load models representation, were ran in an Intel Core i7 2.7 GHz CPU / 8Gb RAM computer.

In the MATLAB-based software the user determines the nominal load data, the generator line voltage value, the line impedance, a minimum voltage variation value to be used as the stopping criterion and the load model representation to be applied, which correspond to the input variables of the software, requested in the user interface. As a result, the program will provide the values of phase voltage, current and apparent power absorbed by each phase of the load, the number of iterations required for meeting the stopping criterion and the program processing time. All the data will be available to the user through the built table.

Furthermore, it will be provided to the user the phasor diagram representing the generator, load and line voltages, according to the selected load model representation. It is important to stress that all results are arranged on the same interface screen, as well as the section in which the input data are entered.

The computational analysis results of the three load models representations applied to the test system, considering power factor variations, are presented in Table 1.

Table 1. Load modelling with different power factor

Power Factor	Variables	Constant Impedance	Constant Power	Constant Current
0.9	V_F (V)	204.70$\lfloor$-3.0°	202.04$\lfloor$-3,51°	203.54$\lfloor$-3,23°
	I_F (A)	42.29$\lfloor$-28,84°	49.49$\lfloor$-29,36°	45.45$\lfloor$-29,07°
	S_F (VA)	8,658.3$\lfloor$25,84°	10,000$\lfloor$25,84°	9252.2$\lfloor$25,84°
	Iterations	-	8	3
	Processing time (s)	0.0726	0.0607	0.1220
0.7	V_F (V)	197.54$\lfloor$-1.87°	191.18$\lfloor$-2.40°	194.98$\lfloor$-2.09°
	I_F (A)	52.47$\lfloor$-47.44°	67.25$\lfloor$-47.97°	58.44$\lfloor$-47.66°
	S_F (VA)	10,366$\lfloor$45.57°	12,857$\lfloor$45.57°	11,395$\lfloor$45.57°
	Iterations	-	9	3
	Processing time (s)	0.00059	0.0045	0.0052
0.5	V_F (V)	188.66$\lfloor$-0.48°	173.73$\lfloor$-0.72°	183.46$\lfloor$-0.57°
	I_F (A)	70.16$\lfloor$-60.48°	103.6$\lfloor$-60.72°	81.81$\lfloor$-60.57°
	S_F (VA)	13,238$\lfloor$60.00°	18,000$\lfloor$60.00°	15,011$\lfloor$60.00°
	Iterations	-	11	3
	Processing time (s)	0.00067	0.00074	0.0093

Table 1 shows the influence of the power factor on the load phase voltage. It is possible to observe that lower power factor values lead to voltage sags. Also, line voltage values were reduced by 8% to 15%. Regarding power quality those values are significant.

Concurrently, note that the power factor reduction considerably increases the current absorbed by the load. The value of the current ranges between 40% and 50% in the three representation models, which implies in greater losses and warming of conductors.

Concerning the constant current model, it is verified the veracity of the results before the theory for the three simulations. It is noticeable the increase of the current value against the reduction of the voltage.

Power factor reduction reflects an increase in the system reactive power, which means higher losses and lower efficiency, i.e., undesirable operating state.

It is also noteworthy that the validation of the results presented in Table 1 is corroborated by noting

that in the constant power load representation model the single-phase powers obtained correspond to the nominal single-phase load powers, and in the constant current model the power factor obtained through the simulation is the same as previously established.

The following figures show the result for the phasor diagrams according to the user's choice concerning the desired load representation model.

Initially for the power factor equal to 0.9 and considering the constant impedance representation model, the diagrams presented in Figure 4 are obtained.
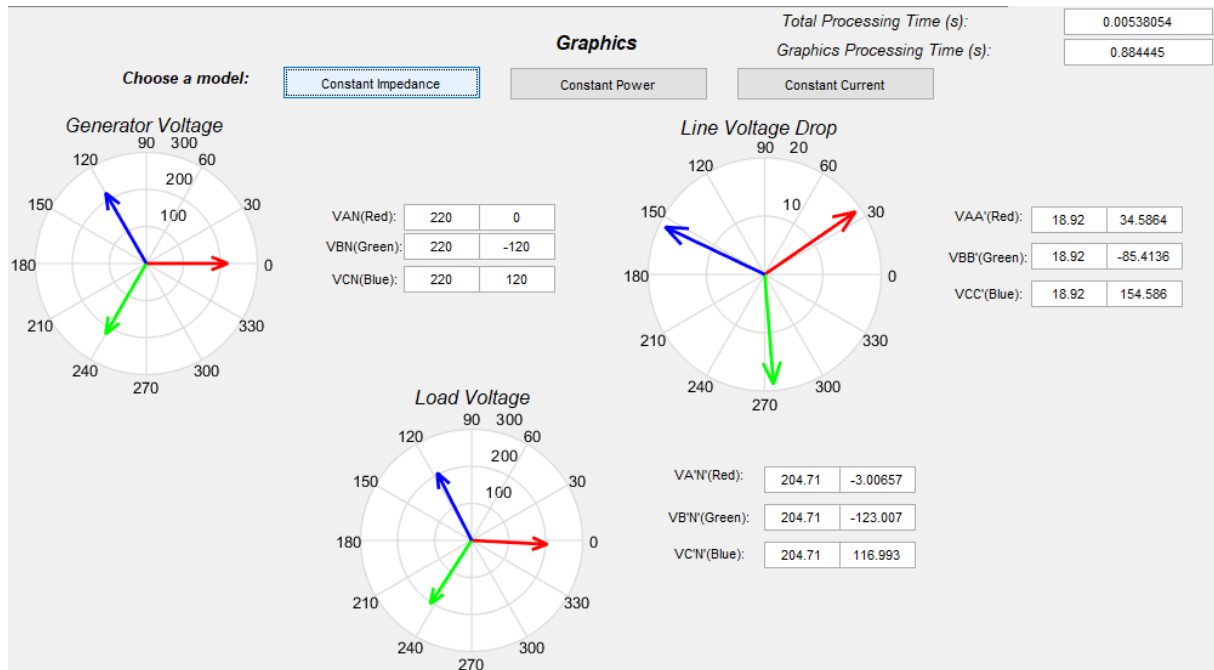
Figure 4. Phasor diagram for constant impedance model considering $cos\varphi = 0.9$

Adopting the constant current model considering $cos\varphi = 0.9$, one obtains the phasor diagrams shown in Figure 5.
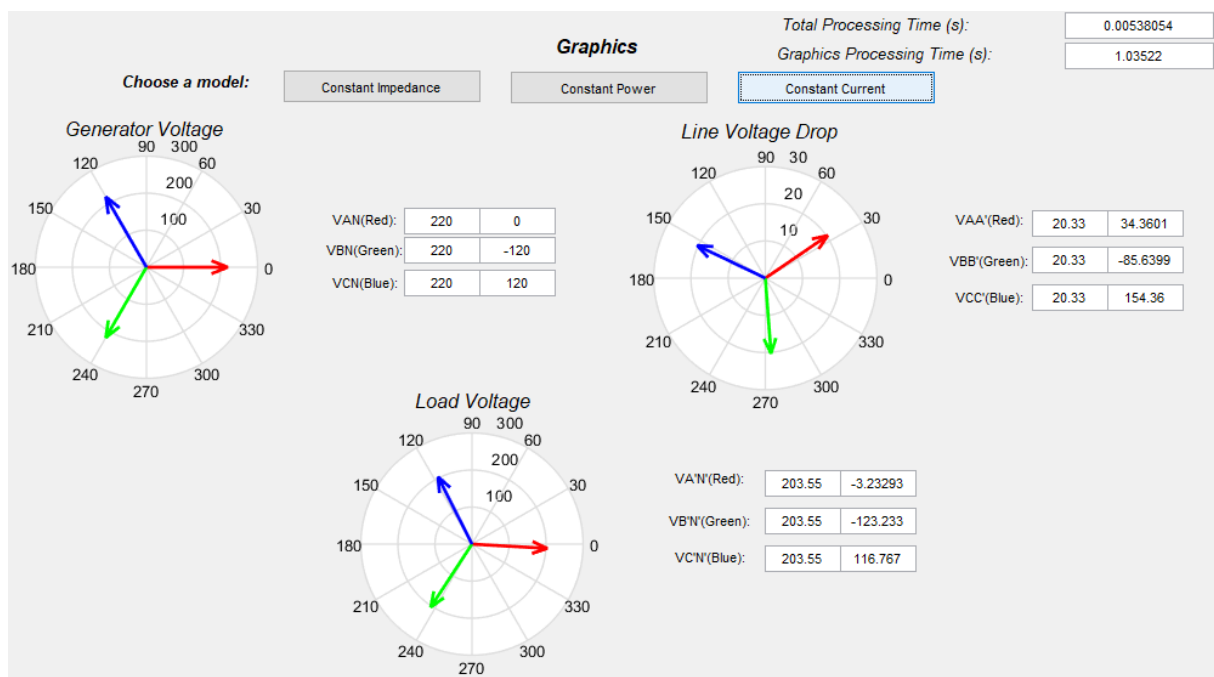
Figure 5. Phasor diagram for constant current model considering $cos\varphi = 0.9$

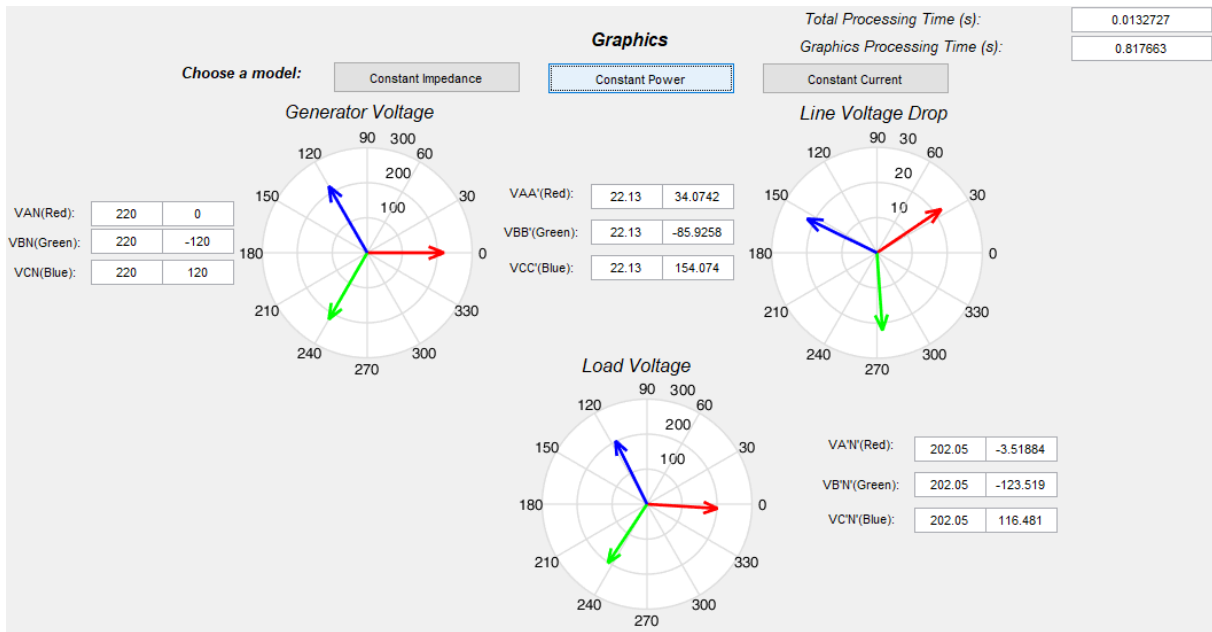At last, Figure 6 shows the phasor diagrams obtained considering the constant power model.

Figure 6. Phasor diagram for constant power model considering $cos\varphi = 0.9$

Further, for a second analyze the power factor is defined equal to 0.7. The phasor diagrams of each load representation model are shown in sequence in Figures 7, 8 and 9.
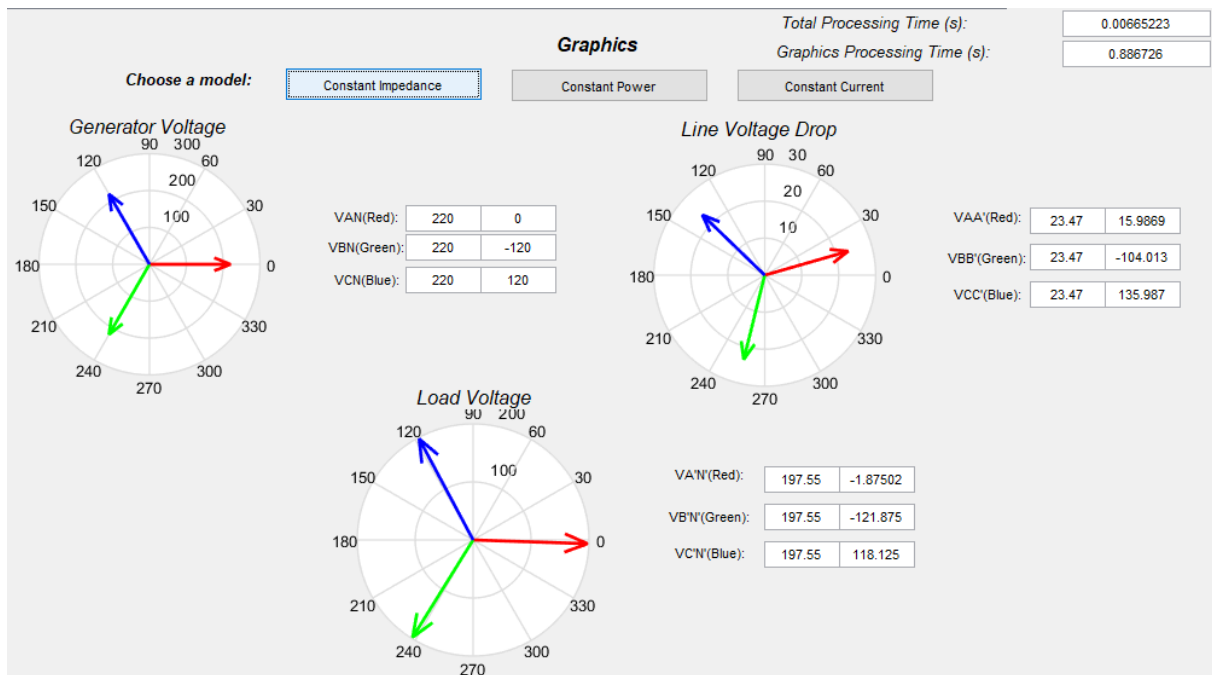

Figure 7. Phasor diagram for constant impedance model considering $cos\varphi = 0.7$
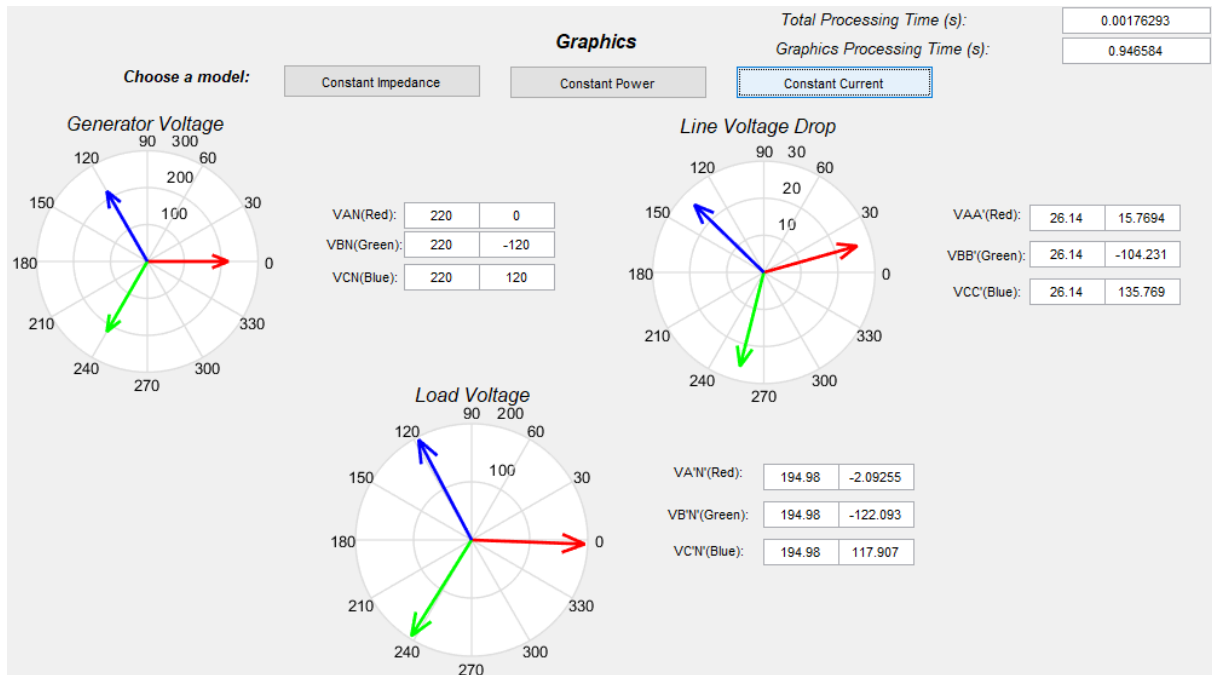
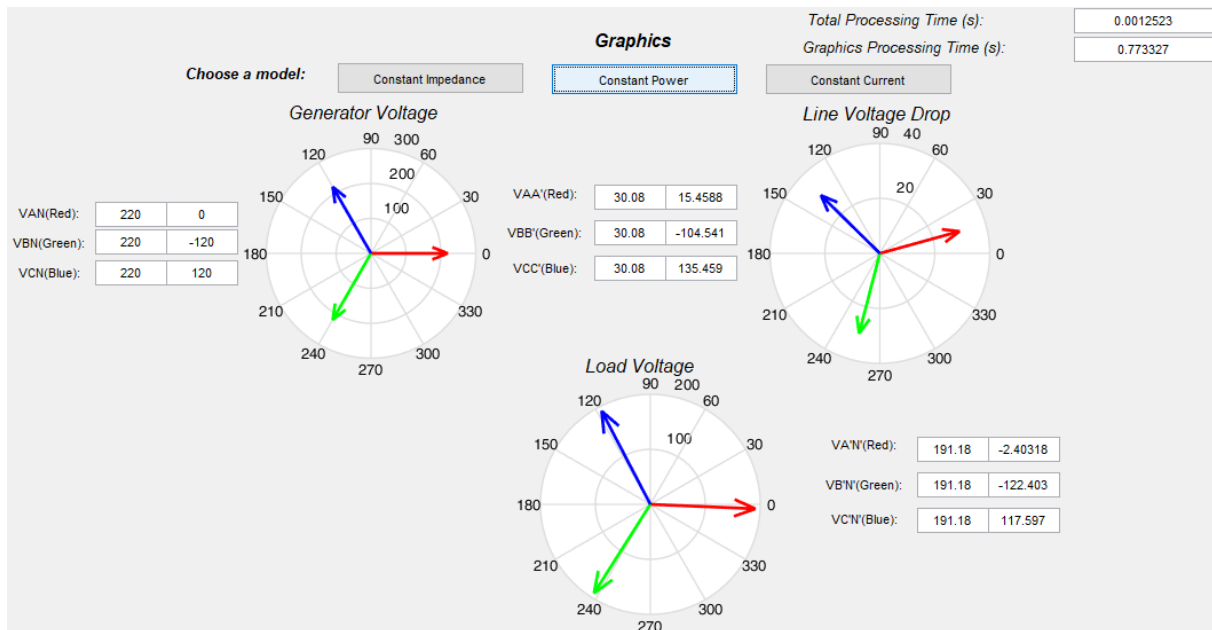Figure 8. Phasor diagram for constant current model considering $cos\varphi = 0.7$

Figure 9. Phasor diagram for constant power model considering $cos\varphi = 0.7$

The last analysis takes place with the power factor equal to 0.5. The phasor diagrams for the three load models are following presented in Figures 10, 11 and 12.
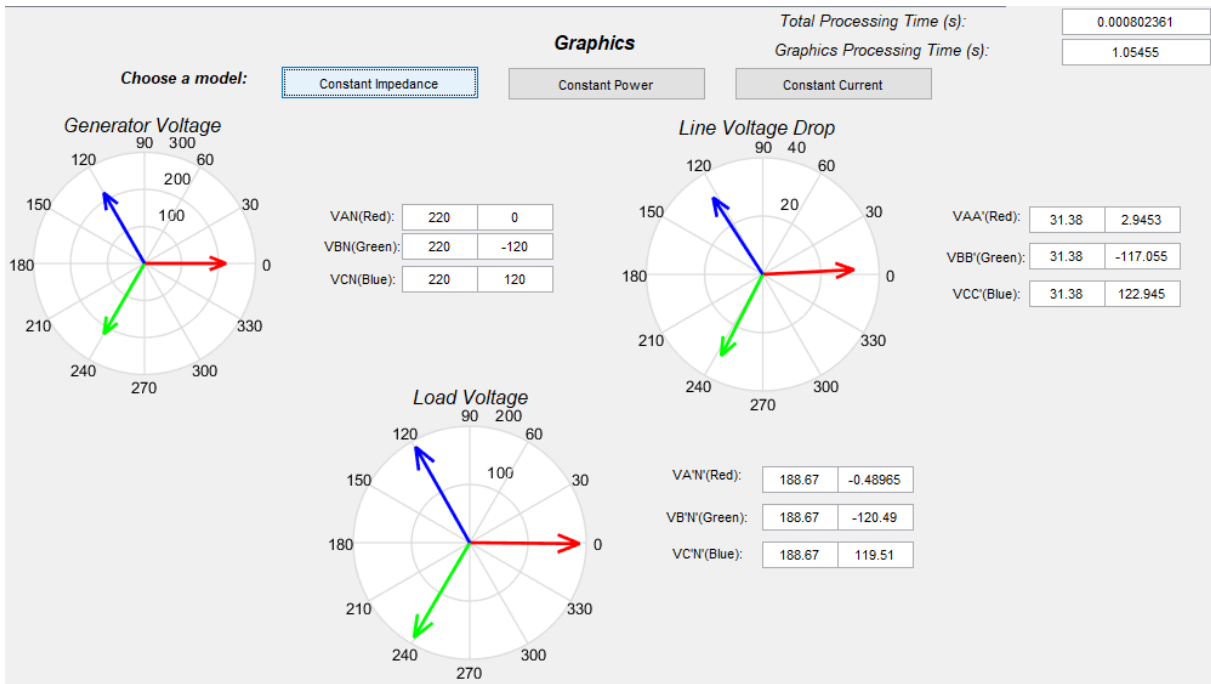
Figure 10. Phasor diagram for constant impedance model considering $cos\varphi = 0.5$.
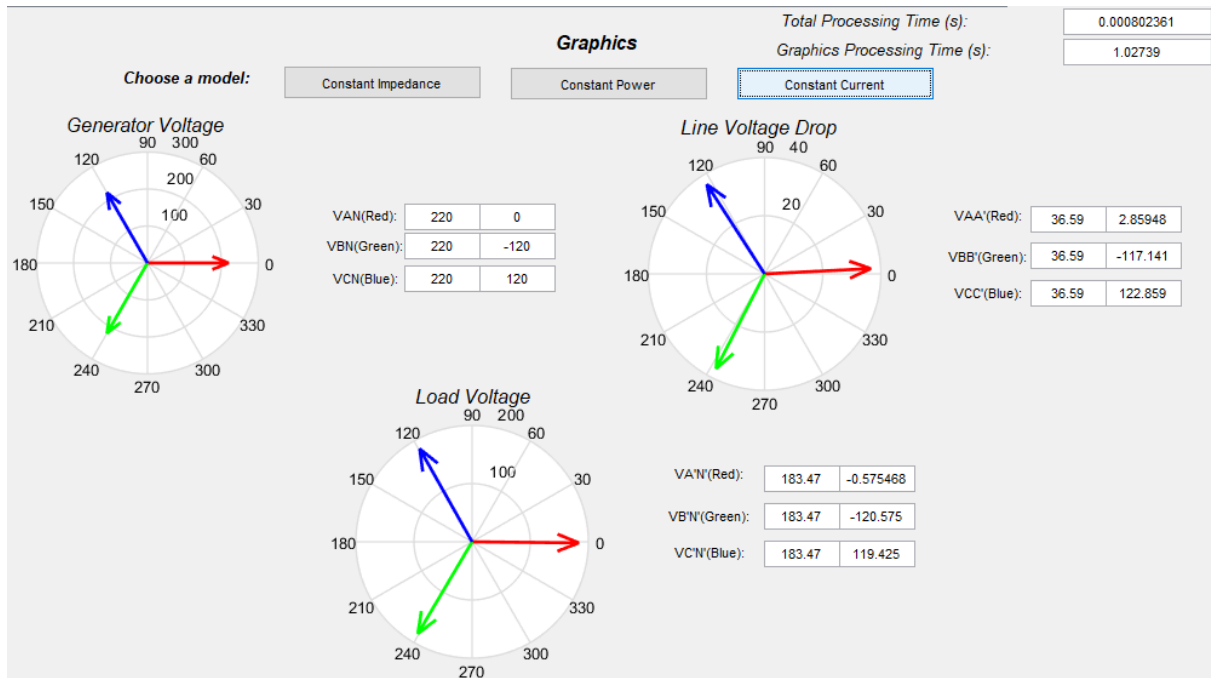

Figure 11. Phasor diagram for constant current model considering $cos\varphi = 0.5$.
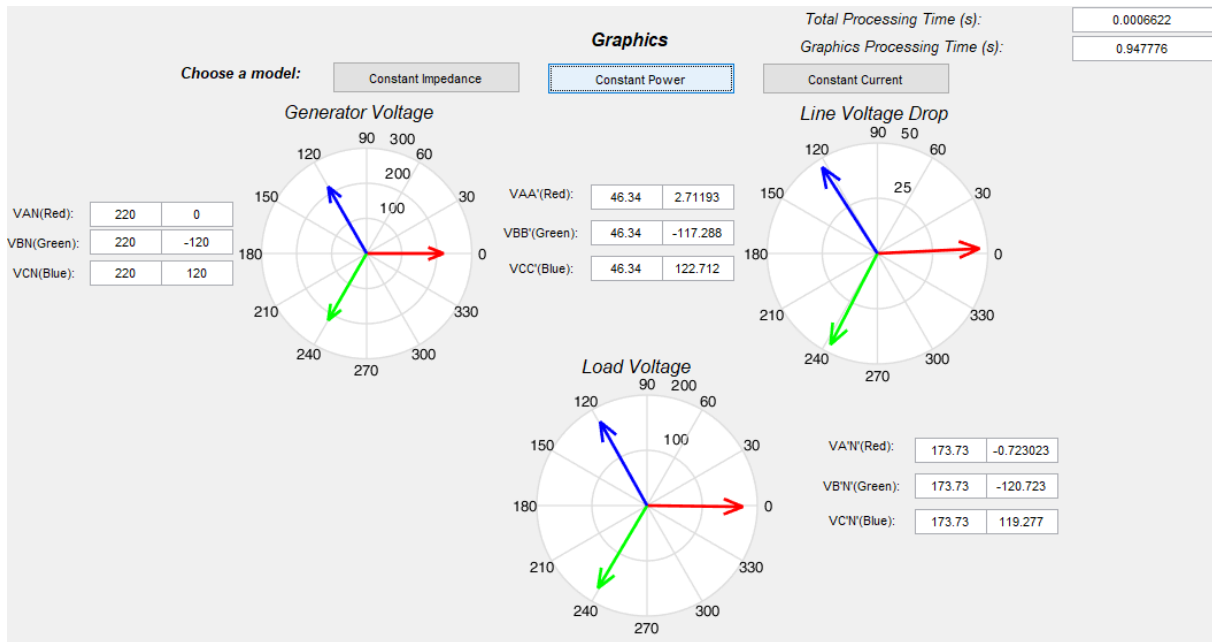
Figure 12. Phasor diagram for constant power considering $cos\varphi = 0.5$.

As seen in Table 1, for the power factor value of 0.5 it is expected to obtain lower voltage values and, consequently, greater line voltage drop values, when compared with previous analyses.

This result was indeed achieved in the phasor diagrams, showing the coherence of the obtained results face to the theory.

Finally, it should be emphasized the efficiency, reliability, reduced number of iterations and computational performance of the tool implemented in MATLAB. The computational time is in the order of milliseconds both for carrying out calculations related to load modelling, as well as filling in the table and displaying phasor diagrams, essential characteristics for the analysis process of electric power systems.

5 Conclusions

The major contribution of this paper is the development of a computational tool using the MATLAB software capable of providing to the user, in an effectively, quickly and reliably way, the voltage, current and load power values of an electric power system considering the representation models of loads, i.e., constant impedance, constant power and constant current.

Correct modelling of loads enables proper planning and operation of electrical systems, providing subsidies that provide more accurate in the studies and analysis for decision making. The results obtained were extremely satisfactory and consistent with those published in the specialized literature. It should be emphasized the possibility of visualizing them in phasor diagrams that are generated by the implemented tool.

Finally, in other hand, another contribution of this work came from the development of proposed computational tool which leads to interdisciplinary projects that prove the effectiveness of knowledge through practices, contribute to the full formation of students and to their motivation. As future works the developed tool can be extended to different scenarios of load modelling. For instance, the load modelling could be obtained by the combination of the three methods used in this work.

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