

Article

# Mathematical Modeling of Electrical Circuits and Practical Works of Increasing Difficulty with Classical Spreadsheet Software

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**Abstract:** This paper presents a modeling practical works project of electrical engineering, proposed to the first-year students of the University Institute of Technology in France, during the COVID-19 pandemic. The objective of this paper is twofold. The first objective is to present to the students the opportunities of modeling and calculation development of a spreadsheet software in their professional lives. The second objective is to create a file that automatically calculates all the current and voltage values at each point of any alternative electrical circuit. The aim of this paper, geared toward students, is to bring them to build their own numerical remote lab, autonomously. Therefore, pedagogical keys are given along the reading of this document to help them to progress, both on electrical circuits conceptual understanding with series and parallel RLC circuits and on their computation in a spreadsheet software. As a conclusion, this paper can be used as a base to develop remote modeling practical works of many and different devices, as well as a database starting point of such analytical models.

**Keywords:** mathematical modeling; analytical models; remote teaching; spreadsheet computation; electrical circuits; student autonomous work



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## 1. Introduction

Since 2020 and the beginning of the COVID-19 crisis, the interest in online works has been exponentially growing. In terms of academic education, online works have become compulsory to some extent. Before this crisis, nobody would have had the idea to propose to undergraduate students to perform electrical engineering practical works online, behind a laptop. However, this worldwide pandemic has profoundly changed humanity within a few days, and organizations, states, and human beings have been obliged to reinvent their ways of life, separated from their loved ones.

Even if the review paper written by Mazlan et al. globally concludes that emergency remote teaching is OK for tertiary institutions [1], the breakdown of pedagogical continuity is something difficult to accept. What was impossible before has become possible in a blink of an eye. Another review paper proposed by Stewart mainly points out, after the first Emergency Remote Teaching (ERT) shock, differing stakeholder priorities and mental health issues [2]. Changes in teaching modalities, course workload and evaluation, and necessary adaptation to a completely different paradigm appear secondarily.

This paper proposes a solution to quickly adapt to a remote teaching situation. It gives a turnkey project for electrical circuits' practical works, with all the necessary matter for an undergraduate student to develop a circuit simulator, with only a simple spreadsheet software (Excel for instance). The need for ways to motivate and engage students and to address the loss of hands-on learning opportunities has been reported by many teachers in a 2020 study conducted by Hamilton, Kaufman, and Diliberti [3]. A practical work of electricity in digital form is proposed in this paper. The way to program the main formulas in a spreadsheet is also explained. Furthermore, the expected results are also presented in some figures. Through reading this paper, the electricity students will not only be able to

recreate their own software environment, with the equations of the various circuits written in a spreadsheet format, but they will also be able to improve it with the modifications they deem appropriate. In the meantime, the autonomous work develops coping skills, very useful to encourage creativity.

Scientific literature on this subject is both scarce and quickly appearing. This is easily understandable, due to the “ancient world” habits, on the one hand, and due to the technological, pedagogical, and social challenges that suddenly appeared, on the other hand [4]. Hamilton, Kaufman, and Diliberti report that students’ engagement and hands-on experience are crucial in a teaching experience and that hands-on learning opportunities need to be addressed [3]. This is the reason why this paper tries to fill in the gap, giving a first version of what could look like an “after world” electrical circuits’ practical work.

After a literature review mainly oriented towards remote teaching and practical work issues, a discussion about remote teaching’s advantages and drawbacks is proposed, as well as an overview of the interactions with the students to overcome their natural reluctance. At the end of this section, the main contributions of this paper are highlighted.

### *1.1. Literature Review on Remote Teaching and Practical Works*

With the pandemic, higher education moved to formats that are not face-to-face classes, and Greenhow and Galvin gave research-based guidelines to inform instructional planning and implementation [5]. The remote teaching to which the world has been forced has led researchers to question the matter of the transition from the classical face-to-face learning to remote learning methods. Since this paper proposes a practical work with the design of a digital remote lab, the literature has also been explored on these subjects. Ultimately, since the aim of the works dealing with educational purpose are geared towards student progress, a point on this topic is also proposed at the end of this literature review.

#### **Transition from face-to-face to remote learning:**

At the very beginning, this transition has suffered from and been performed under emergency conditions [6], but was a pressing need in light of the COVID-19 pandemic [7]. It has also been considered as an innovation strategy opportunity by the Private Higher Education Institution in South Africa [8]. Among works dealing with this subject, an exploratory study tried to understand how the learning was mediated by technology during the early stages of the pandemic and how students and teachers experienced this sudden change [9]. Another five case studies about this change reporting on the resilience of both students and instructors have also been published [10]. The authors also concluded that the delivery mode of the course (synchronous, asynchronous, or blended) does not have any effect on students’ satisfaction or opinion.

Nesenbergs, Abolins, Ormanis, and Mednis aggregated the current knowledge of how virtual and augmented reality technologies are applicable to and impact remote learning outcomes in higher education, such as performance and engagement specifically [11]. A students’ Remote Learning Attitude Scale (RLAS) was developed and validated by Tzafilkou, Perifanou, and Economides [12]. The remote assessment subject was addressed by Senel and Senel [13]. The authors of a case study on the Middle East College, Oman, identified the main challenges in remote assessment to be academic dishonesty, infrastructure, coverage of learning outcomes, and commitment of students to submit assessments [14]. In 2021, Churiyah, Basuki, Dharma, Filianti, and Sakdiyyah gave some design keys for mobile learning applications, with performance-based authentic assessment [15].

The student’s attitudes and perceptions were studied in a work dealing with the transition from face-to-face to remote learning performed by Serhan [16], as well as the teaching improvement of faculty members through reflection about this crisis’s opportunities in a paper written by Hodges and Fowler [17]. Hodges, Moore, Lockee, Trust, and Bond highlighted a difference between emergency remote teaching and online learning [18].

Among the drawbacks reported about remote learning, the most obvious is the remoteness [19]. Greenhow and Galvin proposed strategies to overcome this drawback [5]. Positive cognitive, behavioral, and affective learning outcomes in higher education were

reported in a study published by Post, Guo, Saab, and Admiraal [20]. Ultimately, a question about the actual working of all these efforts was asked by June, giving the opinion of higher education [21].

#### **Practical works:**

Practical works are very important in the educational process, at any age [22]. Their reliability has been questioned [23], is still questioned [21], and will continue to be questioned because this concept is expansive, in terms of material, maintenance, rooms with only partial occupation, smaller groups, etc. The question of its effectiveness has also been treated [24]. Abrahams and Reiss reported that practical work might be made more effective, in terms of developing students' conceptual understanding if teachers adopted a more "hands-on" and "minds-on" approach and explicitly planned how students were to link these two essential components of practical work [22].

Distance practical education has been tested on power electronics [25], for the design of a flyback converter [26], for the dynamics of linear electrical systems [27], for a drive system with an elastic coupling [28], for geography [29], for medical sciences [30], for analog electronics [31], and for physical and engineering sciences [32]. On a different basis, since the coupling of electrical circuits with 2D and 3D computational domains is important for practical applications, light was pedagogically shed on the definition and on the physical meaning of voltage in the case of time-varying quasi-static fields in a recent paper written by Scoretti [33].

#### **Remote labs:**

A remote lab is defined as the remote control of a physical lab within the walls of a university. Students perform the control from distant equipment, physically located in a laboratory. In parallel, scientific research on remote labs in these disciplines has largely increased. Remote labs have developed in higher education over the past 15 years, especially in computer science and engineering education, as reported in the recent review paper written by Post, Guo, Saab, and Admiraal [20]. The benefits are substantial: lower costs, 24/7 availability, accessibility for disabled students [34], and the possibility of a remote collaboration and cooperation, even abroad. Moreover, many cognitive and behavioral outcomes have been proven to be positive in most of the related papers. By themselves, remote and virtual labs contribute also to higher education improvement [35].

#### **Gains for students:**

Students gained conceptual knowledge. Chen and Gao reported better programming skills and grasp of the concepts [36]. Sauter, Uttal, Rapp, Downing, and Jona remarked that students were more deeply engaged while working with the remote lab. They felt and behaved as though they completed a real scientific experiment [37].

Thanks to its availability [38], usefulness and usability [39], and acceptance [40], students are more engaged in the lab. This experience is also reported to be challenging and interesting, and students declare having learned more than expected in comparative experiences conducted by Boix, Gomis, Montesinos, Galceran, and Sudrià [41]. They also declared a gain in curiosity and motivation, compared to what would have been the case with a hands-on practical work in a study performed by Jara, Candelas, Puente, and Torres [42].

Students are also satisfied with learning in a remote lab context. They are especially positive about collaborative learning and autonomous activity [43]. Another reported on students' satisfaction with remote labs being due to the "anywhere anytime" accessibility, innovative experiments, improved confidence level of teaching, and usefulness for learning and teaching [44].

### *1.2. Advantages of Remote Teaching*

Some positive aspects of the recent remote teaching experience have been reported in a paper dealing with Portuguese teachers, such as competence development, opportunities to develop new works and interactivity with students, evaluation, and learning [45].

In the following lines, I propose some personal thoughts about the positive aspects of remote learning:

- (i) There is much interest in developing practical work online. As far as practical work is concerned, until now, it was not possible to perform it anywhere else than behind wires and a mock-up. Thanks to remote teaching tools, it is now possible to use computer programs for teaching purposes.
- (ii) The safety of the students is ensured. This point is very important, because practical work in power electronics is very often performed in the presence of dangerous voltages. Obviously, the teachers who supervise these sessions are always very vigilant, and the sense of responsibility they feel during these sessions is something that is rarely taken into consideration. Nevertheless, this point can be improved through this system of remote practical works.
- (iii) In addition, the study and analysis of curves, which usually tends to be overlooked by students, can take on an increasing role in the work that can be asked of students. The mere wiring does not risk being considered as a sufficient output. Indeed, during conventional practice sessions, the teacher's attention is much more focused on the aspects of practical accomplishments in the session than on the study and comments of the curves that can be drawn from the practical work sessions. Students' working hours can be focused on spending the necessary time to understand the considered phenomena. During the scheduled synchronous activities initially devoted to "real" practical works, collaboration among students and one-on-one or small group discussions between students and faculty member, as recommended by Seabra, Teixeira, Abelha, and Aires, are possible [45].
- (iv) Moreover, this new work organization gives to the students and to their teachers a new flexibility parameter: the opportunity to work asynchronously, i.e., not necessarily at the same time as during the teacher's time online. With the matter contained in this paper, the purpose of which is to be widely disseminated, copied, and distributed to the students who need it, one can imagine that the teacher gives this reference to the students and asks them to study it, to try to perform the proposed work alone, and finally, to meet remotely in the classroom to ask any remaining and useful questions. Ideally, the goal of this paper is to reduce these remaining questions to their minimum.
- (v) Furthermore, with asynchronous work, students can deepen the topics and are no longer limited by the duration of the sessions as when they take place in a face-to-face context. They will be able to keep track of this paper to deepen the points that they may not have had time to deepen during the session [46].
- (vi) In the long term, writing this practical work tutorial paper and proposing it to the world will provide a basis for the standardization of electrical engineering teaching practices, thus being a seminal work for international online university standards' creation.

### 1.3. Drawbacks of Remote Teaching

Obviously, negative aspects have also been reported. For example, in the Philippine higher education institutions, the study of Abel revealed four main themes of concern: poor to no Internet access, financial constraints, lack of technological devices, and affective or emotional support [47]. Interestingly, the findings showed that learning remotely in these trying times is challenging because, aside from the existing problems of access and affordability, the emerging concerns of financial stability and affective support unfortunately contributed to interrupted learning engagement. Another work proposed by Shin and Hickey revealed not only that the participants have experienced learning loss and lack of motivation, but also that the preexisting educational and social inequities seemed exacerbated and amplified during ERT and the COVID-19 crisis. Issues in terms of accessibility, the digital divide, inequity, and mental/emotional/physical health that the participants experienced during emergency remote learning were especially concerning [48]. The results highlighted the importance of addressing and combating the inequities, creating

and maintaining a sense of community, and most significantly, providing socio-emotional support and compassion to college students and their instructors during the uncertain times. This support is defined as “*Tender Loving Care*” (TLC). “*Tender Loving Care*” is an expression describing extra attention to make someone or something look or feel better. In the following lines, I propose some personal thoughts about the negative aspects of practical works’ remote learning:

- (i) Of course, the main drawback of this new pedagogical method is the impossibility for the student to practice on electrical circuits “with hands”. This disadvantage is major, but it is a presupposition of the work proposed in this paper. To the extent that nobody knows whether a crisis like the COVID-19 will ever be repeated, it is prudent to provide alternatives to the classical and traditional teaching methods, as we have known for more than a century. On the other hand, as this method is totally new, it is difficult to imagine any other drawbacks today.
- (ii) As is often the case with education, Good Practices are acquired through experience. Since this method is completely new, we have no data from experiments. Thanks to the feedback that will be communicated to me by colleagues who would have put this new teaching method into practice, it will be possible in a few years to write a new paper with a feedback synthesis about this practice.

#### 1.4. Justification for the Use of Excel (or an “Excel-like”) Spreadsheet Software

Many reasons support the use of the Excel (or “Excel-like”) spreadsheet software. They are summed up and pointed one by one in this section:

- (i) The first one is the feasibility of the work proposed in this paper. To this aim, the accessibility to a spreadsheet software is crucial. We assumed that all the students to whom we will offer to perform this work remotely have, on the one hand, Internet access so as to be able to download the article and, on the other hand, an Excel-type software in order to be able to validly download the attached example file and, above all, to be able to work on it.
- (ii) Excel is a spreadsheet software that is found in the office suite Microsoft Office. This software is designed and distributed by Microsoft to run on digital devices of almost all major manufacturers. It includes facilities in terms of numerical calculation, data analysis, graphic presentation, and programming.  
Excel is the best-known spreadsheet software by professional companies, and it has real advantages for all users, including the less experienced, because it is very quick to set up and very easy to use. Therefore, more than the indubitable advantages offered by its ubiquity and availability, the offered possibility to progress on your own is very interesting also.  
More, since many people are experienced in using this software, a remote student is able to find any help around (parents, brothers and sisters, friends, etc.). Finding help to progress is not as difficult for a spreadsheet software as any other software used by fewer people.
- (iii) In addition, the special characteristics of these software support their use. All data are available on a single page, for simplicity. Furthermore, the modulation of the form and content are easy to perform, for the flexibility of both presentation and management of the data. Moreover, no additional user license cost needs to be paid, because Excel is generally part of the Office license, which is furthermore free for students. This support the universal use of the software and universal access to modeling.
- (iv) The modeling results obtained by the students after their work can be directly evaluated, precisely because this software is used and easily understood by a majority of professionals. Therefore, students are encouraged to work beyond the limits of the practical work proposed in this paper and to evaluate their work with a demonstration during a job meeting, for example.

Obviously, Excel is not a “miracle” software, and some drawbacks for the use of such a software exist and are listed below. Anyway, these drawbacks have been estimated as insufficiently negative with regard to its advantages for the particular aim of the practical work proposed in this paper:

- (a) The follow-up of a project can be difficult with such a software, even if the addition of several lines of comments is possible. It is clearly not enough, both for the follow-up of a modeling and its instantiating on multiple projects based on the same model. In addition, each new comment is unfortunately not dated automatically, hence the difficulty of having a scrupulous follow-up of the history of a model.
- (b) When working with an Excel-like spreadsheet software, one is nearly obliged to create a file per each need. Thus, with each new industrial need, whether in terms of quotes, purchases, invoices, follow-up management, project management, or time management, it is necessary to create a new file, which causes a loss of time to find the files and fill them in.
- (c) The interface of such a software is limited. The more information you want to save, the more columns or spreadsheets there are, which with use ends up losing readability. This is all the more limited as data reading can only be performed in a table format.
- (d) To conclude, when this software is practical for specific needs, the Excel software is quickly overtaken by professional software, specifically designed to meet certain needs that are much more suitable for professional everyday needs. They automatically perform calculations and automatically generate the documents that companies need. Sometimes, they can send email notifications or highlight the most relevant information.

#### 1.5. Frequently Asked Questions from the Students and Typical Answers

Tsai, Rodriguez, Li, Robert, Serpi, and Carroll conducted a qualitative study on how the pandemic was experienced at the University of Pennsylvania, in which they reported several testimonies of the experience of students and teachers [49]. The three main axes of works for improvement they identified for the future were: first, the inclusion of student and faculty collective experience, which is a largely under-explored research question in the remote education domain; second, the investigation of digital maturity or resilience in quickly transitioning conventional curriculum to a remote or mixed-mode learning environment; third, the further understanding of the impact of quarantines on post-pandemic learning and teaching, because the pandemic may permanently change the expectations of future learners and instructors.

This article is based on an actual experience that took place with students in the middle of the COVID-19 epidemic. Therefore, in addition to the legitimate fears that weighed on the general population, the students were concerned about what this experience could bring or take away from them compared to what was the case in previous years. In the following lines, some question/answer sentences directly taken from this experience with the students on this particular practical work are given to help teachers or students take the leap.

**Reluctance of students:** Reluctance is a normal behavior in the face of novelty, for students as for anybody else.

- “Sir, we’re not going to make it!”
- “This is normal, you’ve never made professional files on a computational software. It is not only okay, but it’s a chance for you to get the opportunity to start in school. This file, you do it for yourself. You give me your job at the end, but it is more with a goal of verifying the amount of personal work you have invested in it than to evaluate your work... Not only you do keep the file at the end of the practical works series, but most importantly you **keep the ability to improve it** throughout the rest of your life, in the way you deem useful”.

**Working atmosphere:** During these works, students are allowed to share information.

- “Just as employees share information in the company to evolve the tools they create for it, you can share information you deem appropriate, to help you to progress in your work”.

Initially, I provide the example of the work done with the RLC series circuit, presented in the next section. With this first sheet, students better understand **what** they are asked to do **and how** they can manage to get by.

- “I give this tutorial work to show you how the knowledge you have learned in courses and tutorials is articulated between the different parts of the spreadsheet software”.

**Added value:** At the very beginning of its presentation, students may doubt the merits of this practical work as a new practice.

- “It would be better for us to practice with real material. This distance from the practical work room will put us at a disadvantage compared to students who have worked on “real material”.
- “This given job gives you a plus for your resume. Indeed, in front of a recruiter, you will be able to present the result of your personal work, which you can specify that it was initiated in the school setting.”

Furthermore, this kind of work, directly usable in an industrial environment, may prevent some from saying the too frequently heard, too easy, and too inaccurate sentence: - “You don’t learn anything at school !”.

#### 1.6. Contributions of This Paper

Since the practical work presented in this paper is to be realized remotely, the benefits from the remote labs’ literature are also to be expected. The main contributions of this paper are presented below.

##### **For the teachers:**

- (i) This paper gives a **positive example of what can actually be done** in terms of remote learning with a class. Indeed, the papers published in the literature deal with social or exploratory aspects, but very few give examples of what a teaching sequence should look like.
- (ii) Additionally, **a real model** of what this paper deals with **is given alongside this paper**. The experiment reported in this paper is illustrated with an Excel file, available on the MDPI website database.

##### **For the students:**

- (iii) This paper is a **“do it yourself”** proposition made to the students. Indeed, this paper can be loaded as a subject of remote practical works or also possibly a project supervised by a tutor. This proposition is also an originality of this paper, and the promise of autonomy contained in this project further motivates the students, who want to get involved in such projects, which become personal to them. They usually enjoy this kind of proposition and take it to prove what they are able to do.
- (iv) Additionally, the **“keep it yourself”** pledge is given to the students. The model given in the database is indeed completely loadable by anybody, but its complete understanding, control, and modification possibilities are directly linked to the skills that will be developed by each student, not only during the practical work activity, but even after, if the student decides to keep, maintain, and improve this file.

This paper is organized as follows. In Section 2, a first approach is proposed, with the respective series and parallel RLC circuits’ modeling and simulation. Section 3 takes a step with the three parallel RLC series branches’ modeling and simulation. Section 4 takes another step, presenting the connection in a series of two complete three parallel RLC series branches’ modules. The Conclusion Section summarizes the benefits and contributions of this paper for both students and teachers, as well as some limitations, and gives some perspectives of this work in two main directions.

## 2. First Approach: Series and Parallel RLC Circuit Modeling

First, the work asked of the students is to model and simulate, thanks to a spreadsheet software, the operation of an RLC circuit. For pedagogical reasons, this work is required to be performed in two stages: the RLC series circuit is modeled in first time and then the RLC parallel one. This repetition helps the students understand both the complex functions in the spreadsheet software and the fundamental difference between a series and a parallel electrical circuit.

In this part, the results that will be presented in the figures for both series and parallel circuits will be the answers of an electrical circuit with the input values presented in Table 1. Thus, the students who will work on the basis of this paper to develop their own spreadsheet will be able to check whether their results correspond to those presented in the appropriate figures.

**Table 1.** Input values for the RLC series and parallel circuit tests.

Variable	Value	Unit
$U_{eff}$	24	V
$I_{eff}$	5	A
$f$	50	Hz
$R$	10	$\Omega$
$L$	150	mH
$C$	100	$\mu\text{F}$

### 2.1. RLC Series Circuit Simulation

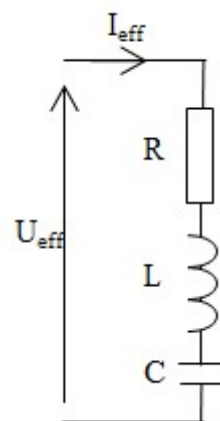
In a series circuit, the electrical state value “seen” by all components connected in series is the current. Then, the model and calculations start with the current value.

#### 2.1.1. Problem Description and Equations

To model an RLC series circuit, the students need to have as the input the three values of  $R$ ,  $L$ , and  $C$  and the value of the frequency  $f$ , which is rapidly turned into pulsation, thanks to the following formula:

$$\omega = 2\pi f, \text{ with } \omega \text{ in rad/s and } f \text{ in Hz.}$$

The only remaining input value needed to completely solve the circuit is either the voltage value  $U_{eff}$  or the current value  $I_{eff}$ , as shown in Figure 1.



**Figure 1.** RLC series circuit simulated.

In this first work, to train the students to design useful spreadsheets in as many different situations as possible, we want to give the possibility to the user to enter as an input either  $U_{eff}$  or  $I_{eff}$ . Then, when the given input is the voltage  $U_{eff}$ , the output values are read on the lines where the calculated values are referenced to with “\_u”. In the same



way, we can read the results of the calculations with  $I_{eff}$  given as the input on the lines where the calculations results are referenced with a “\_i” (cf. Figure 2).

#### RLC serial load supplied with a sinusoidal voltage :

f =	50	Hz	w =	3.14E+02	rad/s						
U <sub>eff</sub> =	24	V	I <sub>eff</sub> =	1.31E+00	A	S <sub>u</sub> =	3.15E+01	VA	cosφ <sub>u</sub> =	5.47E-01	
						P <sub>u</sub> =	1.73E+01	W	Q <sub>u</sub> =	2.64E+01	VAR
I <sub>eff</sub> =	5	A	U <sub>eff</sub> =	9.14E+01	V	S <sub>i</sub> =	4.57E+02	VA	cosφ <sub>i</sub> =	5.47E-01	
						P <sub>i</sub> =	2.50E+02	W	Q <sub>u</sub> =	3.82E+02	VAR

#### RLC taken each separately

R =	10	Ω	P <sub>u</sub> =	5.76E+01	W	Q <sub>u</sub> =	0.00E+00	VAR	I <sub>eff</sub> =	2.40E+00	A
			P <sub>i</sub> =	2.50E+02	W	Q <sub>i</sub> =	0.00E+00	VAR	U <sub>eff</sub> =	5.00E+01	V
L =	0.15	H	P <sub>u</sub> =	0.00E+00	W	Q <sub>u</sub> =	1.22E+01	VAR	I <sub>eff</sub> =	5.09E-01	A
			P <sub>i</sub> =	0.00E+00	W	Q <sub>i</sub> =	1.18E+03	VAR	U <sub>eff</sub> =	2.36E+02	V
C =	1.00E-04	F	P <sub>u</sub> =	0.00E+00	W	Q <sub>u</sub> =	-1.81E+01	VAR	I <sub>eff</sub> =	7.54E-01	A
			P <sub>i</sub> =	0.00E+00	W	Q <sub>i</sub> =	-7.96E+02	VAR	U <sub>eff</sub> =	1.59E+02	V

Figure 2. Results obtained with the RLC series circuit calculating sheet.

#### 2.1.2. Excel Formulation and Results

On a professional spreadsheet, it is essential to clearly separate the input data from the output data. In the left column of Figure 2, the input values are presented on a yellow background, whereas the calculated values are presented on a blue background.

On the line beginning with  $U_{eff}$ , the calculations of  $I_{eff}$ ,  $S_u$ , and  $\cos\phi_u$  are, respectively, the results of  $U_{eff}/Z$ ,  $U_{eff}.I_{eff}$ , and  $R/Z$ , with  $Z = \sqrt{R^2 + (L\omega - \frac{1}{C\omega})^2}$ , as studied in the module course part. Similar results are given on the line beginning with  $I_{eff}$ , with the relevant calculation. Here, the only difficulty is the calculation of a square and a square-root in a spreadsheet, respectively, usually obtained with a “^” and with the “sqrt()” commands in classical software.

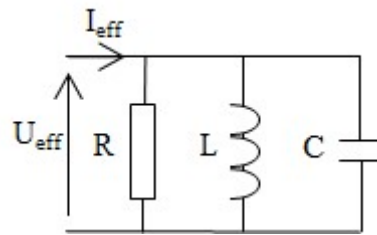
For the complete autonomy of the students, the obtained results are presented in Figure 2. If they are interested in calculating the results of each of the components taken separately, the results are presented in the following lines of the figure, here again calculated either with the input of  $U_{eff}$  or  $I_{eff}$ .

#### 2.2. RLC Parallel Circuit Simulation

In a parallel circuit, the electrical state value “seen” by all components connected in parallel is the voltage. Then, the usual calculations start with the voltage value. The input values taken to test the file are presented in Table 1.

##### 2.2.1. Problem Description and Equations

In this part, the RLC parallel circuit presented in Figure 3 is investigated. Loads are supplied in parallel with sinusoidal voltage. Since each component is submitted to the load voltage, the complete equivalent load can be calculated as the sum of the admittances of each R, L, and C component, respectively, calculated as  $Y_R = 1/R$ ,  $Y_L = \frac{1}{jL\omega}$ , and  $Y_C = -jC\omega$ . The calculations of active ( $P$ ), reactive ( $Q$ ), and apparent power ( $S$ ) are based on the same principles as for the series case (cf. Figure 4).



**Figure 3.** RLC parallel circuit simulated.

### 2.2.2. Excel Formulation and Results

Depending on the series or parallel connection of the load, the formulation of the problem is different. When the load is connected in series, all the load components are crossed by the same current. On the contrary, when the load is connected in parallel, all the load components are supplied with the same voltage. The only place where the formulation with  $U$  and  $I$  is the same is in the component itself.

In Figure 4, as for the preceding series example, the user can indiscriminately choose the total input voltage  $U_{eff}$  or current  $I_{eff}$ . Input and output data are, here again, clearly separated with the same convention (yellow background: input data; blue background: output), and the values referenced with the “\_u” termination were calculated taking into account a voltage supply, while those referenced with the “\_i” termination were calculated taking into account a current alternative supply.  $Z_{eq}$  and  $Angle$  are the only parameters for which these terminations are not allocated, because they, respectively, stand for the equivalent impedance module and angle. These values are independent of the current or voltage supply. Since this paper is the source of a practical work for students, the cells appearing in green color in Figure 4 are those that are free from formulas, so that students can complete them relevantly. Thus, in the Excel file given alongside the paper, those cells are empty, but in the paper, the correct results appear, giving to students a good way to autonomously control their formulas. The fundamental need for calculation results’ control is also an implicit outcome of the new type of practical works proposed in this paper.

#### RLC loads supplied with 1-phase sinus :

$U_{eff} =$	24	V	$R =$	10	$\Omega$		
$I_{eff} =$	5	A	$L =$	0.15	H		
$f =$	50	Hz	$C =$	1.00E-04	F	$w =$	3.14E+02 rad/s

#### RLC serial :

$Z_{eq} =$	1.83E+01	$\Omega$	$P_{t\_u} =$	1.73E+01	W	$Q_{t\_u} =$	2.64E+01	VAR
$Angle =$	5.68E+01	$^{\circ}$	$P_{t\_i} =$	2.50E+02	W	$Q_{t\_i} =$	3.82E+02	VAR
$I_{eff} =$	1.31E+00	A	$S_{\_u} =$	3.15E+01	VA	$\cos\varphi_{\_u} =$	5.47E-01	
$U_{eff} =$	9.14E+01	V	$S_{\_i} =$	4.57E+02	VA	$\cos\varphi_{\_i} =$	5.47E-01	

#### RLC parallel :

$Z_{eq} =$	9.95E+00	$\Omega$	$P_{t\_u} =$	5.76E+01	W	$Q_{t\_u} =$	-5.87E+00	VAR
$Angle =$	-5.82E+00	$^{\circ}$	$P_{t\_i} =$	2.47E+02	W	$Q_{t\_i} =$	-2.52E+01	VAR
$I_{eff} =$	2.41E+00	A	$S_{\_u} =$	5.79E+01	VA	$\cos\varphi_{\_u} =$	9.95E-01	
$U_{eff} =$	4.97E+01	V	$S_{\_i} =$	2.49E+02	VA	$\cos\varphi_{\_i} =$	9.95E-01	

**Figure 4.** Results obtained with the RLC parallel calculating sheet.

For required the continuity and coherence of the first work, the values obtained for an RLC series circuit are recalled in the first output part, and those obtained with an RLC parallel circuit are given just below. Firstly, this presentation clearly shows that the nature of an RLC circuit must be specified in a statement, because the results are visibly different. Secondly, the students who want to see the implications of different variations of each component value on the active and reactive nature of a load can make them vary very

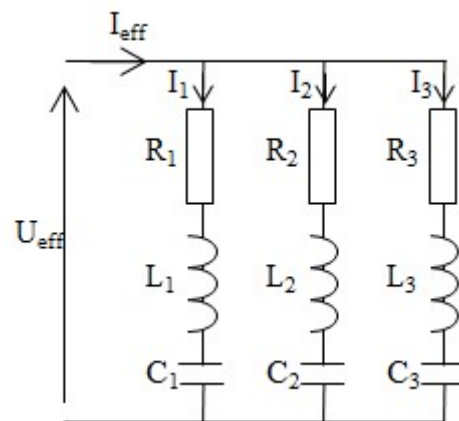
easily and instantly obtain the results. Thus, they will be able to verify and experiment by themselves with the theoretical results presented in the course.

### 3. Three Parallel RLC Branches' Circuit Simulation

In this part, the studied problem becomes more complicated. The power offered by the computation of complex numbers is used to obtain more complex results. Meanwhile, the additional educational objective pursued here is the use of the “complex numbers” function in the spreadsheet software.

#### 3.1. Problem Description and Equations

In this section, the circuit studied is described in Figure 5. It is the connection in parallel of three RLC series circuit branches, as studied in the first part of this paper. The interest in describing such a circuit, with nine unknowns, is to tend towards the general case, which will be the purpose of the next section. All the parameters are referenced as a function of their branch (indexed from 1 to 3) and of their nature ( $R$ ,  $L$ , or  $C$ ).



**Figure 5.** Three parallel RLC branches' circuit simulated.

Ohm's law at the terminals of this load is written as follows:

$$U_{eff} = Z_{eq} \cdot I_{eff}, \text{ with } Z_{eq} = \left( \frac{1}{Z_1} + \frac{1}{Z_2} + \frac{1}{Z_3} \right)^{-1} \quad (1)$$

with:

$$Z_i = R_i + jL_i\omega + \frac{1}{jC_i\omega}, \forall i \in \{1, 2, 3\} \quad (2)$$

Currents  $I_1$ ,  $I_2$ , and  $I_3$  can obviously be obtained with the application of Ohm's law on the terminals of each corresponding circuit branch, with the formula  $I_i = \frac{U_{eff}}{Z_i}$ . Then, their addition thanks to Kirchoff's law is always possible, and it is usually the way used to obtain such a circuit. At this point, any student clearly understands that the direct resolution of the circuit equations passes through the use of the complex numbers' power.

#### 3.2. Excel Formulation and Results

Without the use of the command lines relative to complex numbers, taking into account Equations (1) and (2) could soon become tedious. In this section, basic key knowledge about complex numbers' formulations in classical spreadsheet software are given, so that students can handle them easily. Then, a translation example of Formulas (1) and (2) is given to further help students be autonomous.

##### Complex numbers' formulation:

A complex number is an extension of a real number. It is written “ $a + ib$ ”, with  $a$  and  $b$  being real numbers. To compute such a complex number in a spreadsheet software (such as

Excel), it is sufficient to express it as  $\text{COMPLEX}(a;b;"i")$ . The sums, products, and elevation to a power  $n$  are, respectively, formulated as follows:

$\text{COMPLEX.SUM}(z_1;z_2)$ ,  $\text{COMPLEX.PRODUCT}(z_1;z_2)$ , and  $\text{COMPLEX.POWER}(z_1;n)$ , with  $z_1$  and  $z_2$  two complex numbers and  $n$  a real number.

For the sum and product functions, it is possible to give more than two arguments, each separated with a ";". Thanks to the power function, taking  $n = -1$ , it is possible to obtain the reverse number  $\frac{1}{z}$  of a complex number  $z$  with the following command:  $\text{COMPLEX.POWER}(z;-1)$ . Handling complex modules and arguments can be performed likewise, with the commands  $\text{COMPLEX.MODULE}(z_1)$  and  $\text{COMPLEX.ARGUMENT}(z_1)$ .

Then, to compute in a cell the result of the complex  $Z_1$ , the equivalent impedance of Circuit Branch 1 of Figure 5, as described in Equation (2), the following command directly gives the result, with  $R_1$  in the cell C18,  $L_1$  in C21,  $C_1$  in C24, and  $\omega$  in K6. This line begins with a "IF(C24<>0;"", logical test to prevent any division by zero if the value of  $C_1$  is not entered. In such a case, only the sum  $Z_1 = R_1 + jL_1\omega$  is performed, and the following calculations leading to  $Z_{eq}$  and  $I_{eff}$  are not blocked.

=IF(C24<>0; COMPLEX.SUM(COMPLEX(C18;0;"i"); COMPLEX(0;C21\*K6;"i"); COMPLEX(0;-1/(C24\*K6);"i")); COMPLEX.SUM(COMPLEX(C18;0;"i"); COMPLEX(0;C21\*K6;"i")))

Likewise, to compute in another cell the result of the total equivalent impedance  $Z_{eq}$  of the complete circuit with the three RLC series branches, connected in parallel, presented in Figure 5, it is judicious to use the sum of  $Z_i$  relative admittances  $Y_i = \frac{1}{Z_i}$ . Then, each inverting line can be written as presented in the following command line. With  $Z_2$  in the cell G27, the calculation of  $Y_2$  is obtained thanks to:

=IF(G27<>COMPLEX(0;0;"i"); COMPLEX.POWER(G27;-1); COMPLEX(0;0;"i"))

Then, if at least one component is reported in a branch  $i$ , the relative branch complex impedance  $Z_i$  will be different from 0 and, thus, be inverted with the formula. If not, a complex admittance value of 0 will be noted for the branch  $i$ , thus corresponding to an infinite impedance value. To perform the complete calculation of a circuit, it suffices to write the correct sums and products in the right way. As this paper is intended for possible direct use by students, the formulas allowing coming to the final result are intentionally not given, but the preceding sentence is a good clue.

### 3.3. Results

When the sheet is correctly programmed, with the right formulas in the right cells, any particular RLC circuit corresponding to the general case presented in Figure 5 can be calculated. In Figure 6, the results of the three RLC branches' parallel load circuit are given, so that students can autonomously verify their results. Even if counter examples may always occur, a total correspondence between their work and the results presented in Figure 6 is at least a very good beginning. Since Branch 1 is filled with the components presented in Table 1, the module and argument values of  $Z_1$  obtained in Figure 6 can be compared to those obtained in Figure 4.

In the lower part of Figure 6, the user can enter in the yellow cells the values of the different components (R, L, and/or C), according to those of the electronic circuit studied. Then, from top to bottom, respectively, appear the three different values of currents ( $I_i$ ) with the module and argument, impedance ( $Z_i$ ) with the module and argument, power factor ( $\cos\phi$ ), admittance, and active and reactive power, for the three parallel branches of the corresponding scheme described in Figure 5.

In the central upper part of Figure 6, the total circuit characteristics are given. After a recall of  $U_{eff}$ , from top to bottom, the total current  $I_{eff}$  with the module and argument, the total equivalent impedance  $Z_{eq}$  with the module and argument, the total power factor  $\cos\phi$ , and the total admittance  $Y_{eq}$  are calculated. This way of presenting the calculation and results informs about how the calculation is performed along the sheet and the geometry of the electrical scheme. It was chosen as it is the best possible pedagogically.

3 parallel RLC branches circuit supplied with 1-phase sinusoidal voltage :

0 thr. :	1.00E-09	Ueff	230.00	V	
Ueff =	230.00	Ieff	296354473454i	A	
Ieff =	1.33E+01	Module	1.33E+01	Ω	
f =	50	Argument	-5.08E+01	°	
		w =	314.15927	rad/s	
		Z_eq	22058091302i		
		Module	1.73E+01	Ω	
		Argument	5.08E+01	°	
		cos φ	6.32E-01		
		Y_eq	67585802348i		
I_1	350510484944i	I_2	373792454795i	I_3	377217414376i
Module	1.26E+01	Module	6.20E-01	Module	1.48E+00
Argument	-5.68E+01	Argument	8.23E+01	Argument	-1.47E+01
R_1	10	R_2	50	R_3	150
L_1	0.15	L_2		L_3	0.125
C_1	1.00E-04	C_2	8.66E-06	C_3	
Z_1	29011854678i	Z_2	363378965116i	Z_3	99081698724i
Module	1.83E+01	Module	3.71E+02	Module	1.55E+02
Argument	5.68E+01	Argument	-8.23E+01	Argument	1.47E+01
cos φ	5.47E-01	cos φ	1.35E-01	cos φ	9.67E-01
Y_1	145697760627i	Y_2	119040197737i	Y_3	337920614946i
P	1.58E+03	P	1.92E+01	P	3.30E+02
Q	2.12E+03	Q	5.45E+01	Q	3.35E+02

Figure 6. Three RLC branches connected in parallel circuit calculation sheet.

4. Three RLC Branches Associated in Series with Three Other Parallel RLC Branches' Circuit Simulation

In this part of the practical work proposed in this paper, the aim is to make students understand:

- (i) The power of the results obtainable with a computer, as long as it is well programmed with a correct and precise model;
- (ii) The increasing difficulty of correctly designing a model when the problem is becoming more and more difficult;
- (iii) Thus, the relative confidence one can have about the results, as function of the working power invested.

Meanwhile, at the end of this step, students understand that no problem is too difficult to be tackled. One just has to break it down into several easier problems and then cleverly combine the answers.

4.1. Problem Presentation and Equations

As can be seen in Figure 7, the studied circuit is composed of the series connection of two modules similar to the one studied in the preceding section. Then, as before, any  $RLC_{i,j}$  equivalent impedance of a circuit branch is given by Equation (2). Furthermore, the  $V_2$  voltage equation in function of Load 2 is given by Equation (1). The main difference between this circuit and the preceding one is obviously the presence of Load 1, which makes the calculations of  $I_{RMS}$  and  $V_2$  as function of  $U_{RMS}$  difficult.

However, by modeling each of the two big parts of the circuit with their respective equivalent impedance  $Z_1$  and  $Z_2$ , the complete circuit resolution becomes easier. The two equations allowing solving the circuit's unknowns are then, first, Equation (3) giving the value of  $I_{RMS}$  as a function of only  $U_{RMS}$  and the 18 RLC input values of the problem. Second, when  $I_{RMS}$  is known, it becomes easy to compute  $V_1$  and  $V_2$  with Equations (4) and (5).

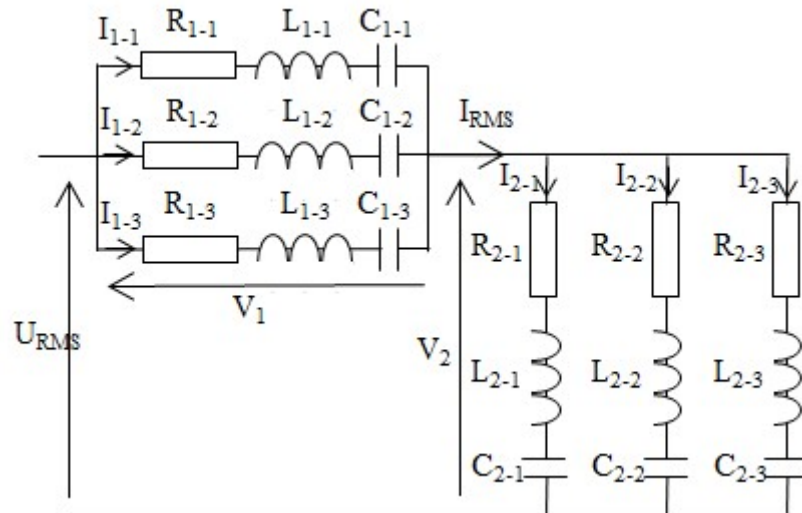
$$I_{RMS} = \frac{U_{RMS}}{Z_1 + Z_2} \tag{3}$$

Then:

$$V_1 = Z_1 I_{RMS}, \text{ or } V_1 = \frac{Z_1}{Z_1 + Z_2} U_{RMS} \tag{4}$$

$$V_2 = Z_2 I_{RMS}, \text{ or } V_2 = \frac{Z_2}{Z_1 + Z_2} U_{RMS} \quad (5)$$

Since all the variables presented in the above equations are complex, the use of the complex functionality in the spreadsheet software becomes compulsory here, under the penalty of too great a complexity to manage.



**Figure 7.** Three RLC branches associated in series with three other parallel RLC branches' circuit simulated.

#### 4.2. Excel Formulation and Results

The formulation of the problem in the Excel file is geometrically visible in Figure 8, in which the results for a particular load are presented. Indeed, on the bottom right of this figure, the geometry of the result presentation of Figure 6 is recognizable and corresponds to the global  $Z_2$  load. Furthermore, this geometry is repeated for the global  $Z_1$  load, on the left of Figure 8, slightly higher. Then, with the respective values of  $Z_1$  and  $Z_2$ , the global calculation of  $I_{RMS}$ ,  $V_2$ , and  $V_1 (=U_{RMS} - V_2)$  is relatively easy to model, thanks to Equations (3)–(5). This part of the calculation is framed in Figure 8 for an easier reading. Since this part of the calculation of the model is crucial, it is given in blue color, and the formulas are in the loadable file. After this first main calculation level, when the module, argument,  $\cos\phi$ , and  $Y$  of all the branches of the circuit are calculated, their power and reactive power can also be calculated, just as well as for the precedent circuit.

Since all the calculation is performed with complex numbers, some results supposed to give 0 can sometimes turn out to be infinitesimal numbers in a cell. To avoid this drawback, a threshold value is introduced at the top of the sheet, put in this example at  $10^{-9}$ . Then, when no load is reported in the  $Z_1$  cells, the difference  $U_{eff} - V_2$  can easily be put to 0, thus clearing all the cells in the  $Z_1$  calculation zone and facilitating reading and understanding of the results.

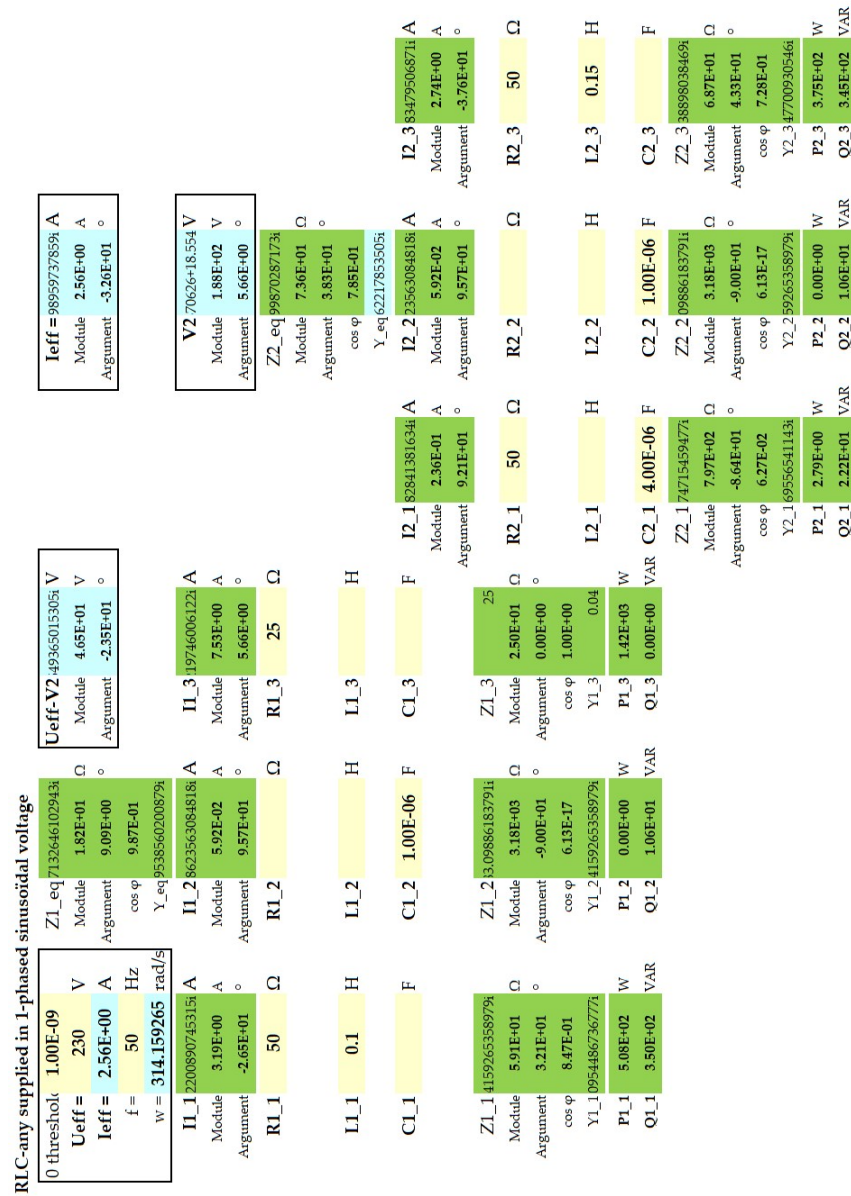
#### 4.3. Particular Case Study and Results

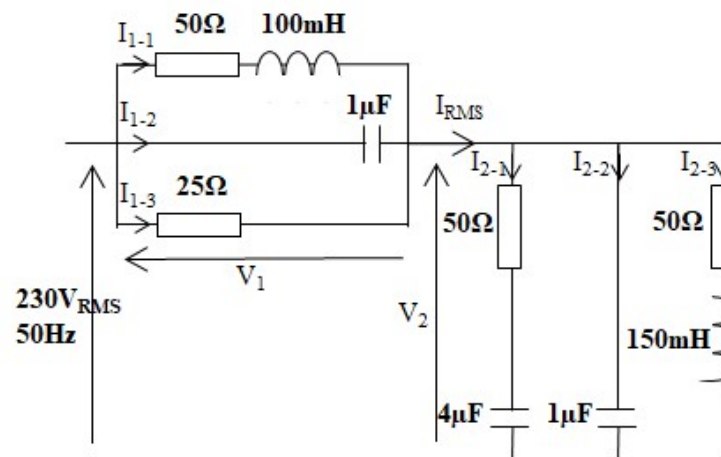
As promised at the beginning of this paper, the reader is now able to give directly any relevant value of any electrical circuit, thanks to the work realized all along its reading. With the twofold aim to prove this and to verify the formulas programmed in the last software sheet, a particular circuit of the general case described in Figure 7 is proposed in Figure 9.

The presentation of the electrical scheme of the particular example given in Figure 9 is asymmetrical to speed up its correspondence verification of the general case proposed in Figure 7.

The study of this particular problem can obviously be performed in an exercise, during a tutorial for example. In this case, the student is invited to measure the time it takes to solve the exercise, with “classical” means.

If the green cells of the original file have been correctly filled in, the complete results appear at the time the last input data are entered. The corresponding results are presented in Figure 8.





**Figure 9.** Particular case proposed to students to verify their formulas.

## 5. Conclusions and Perspectives

### 5.1. Conclusions

To conclude, thanks to this work on a classic spreadsheet, the students learn to use this software better, with the application of some electrical formulas learned during the lessons. The spreadsheets resulting from this work calculate any associations of the RLC circuits, first for a series RLC circuit, then for an RLC series and parallel circuit, next for “any” RLC circuit, and for a series association of any RLC circuits. In addition, they calculate the currents in all parts of the circuit, as well as the partial impedances and admittances. They also calculate the active and reactive powers (respectively,  $P$  and  $Q$ ) in all parts of these series/parallel electrical circuits.

Some of the main outcomes from the students point of view are as follows:

- (i) These sheets put theory into practice by using the different formulas learned in classical courses and allow them to check their good understanding of the notions and to deepen their knowledge.
- (ii) After this experiment, some students have declared having strengthened their curiosity, as well as having worked on this project more than for any other, because they “felt free”.
- (iii) Moreover, the students were proud of their results. They managed to create a useful tool to calculate, without the possibility of error after a serious check, the solutions of any complicated electronic circuit problem.
- (iv) As a result of this momentum, they are greatly encouraged and inspired to create new sheets for very different problems in the future. Likewise, they recognize having acquired a new way of working.
- (v) This paper gives one teaching material, ready-to-use, for the next dreaded precipitated transition to emergency remote learning, thus answering a point raised by Tsai et al. [49].

To the best of my knowledge, this paper is the first one of this type, constituting a real innovation. I am convinced that it could inspire many researchers to design such practical works, towards both goals of making students progress in a given subject and making the general population better at modeling. The possibilities offered by such a paper are infinite, and I profoundly hope that this paper will be the foundation of a research path towards the objective of capitalizing knowledge in many fields, as well as their modeling opportunities.

### 5.2. Limitations

Among the limitations that can be found in this paper, we can mention the following:

- (i) The classical remote teaching drawbacks are all globally applicable to the project proposed in this paper. We can here mainly recall the darkest ones: technology obstacles, social and educational inequalities being exacerbated and amplified [48], and mental health problems.



- (ii) For the proposed practical work by itself, even if it comes from the remote work hypothesis on which this paper is based, a second limitation deals with the fact that students will thus not practice on an actual electrical circuit, nor experience actual dangers linked to electricity cabling and measuring activities.
- (iii) A third limitation deals with the limits of a model itself. In essence, a model is strictly only able to model what it is supposed to. Thus, even the last model is not able to model an electrical circuit composed of two R-C filters in cascade. When one disposes of a model, it becomes always possible and easy to find the cases that are *not* taken into account. One of the objectives of this paper is to give to the students the keys to model any other electrical circuit they will come to during their professional career.
- (iv) The fourth limitation I can see to this work is a threat to the higher education system of Western countries, trying to save money by relying on the new technologies and innovations. Indeed, if this idea were to work too well and exceed the legitimate expectations related to the training of students, as well as the improvement of the modeling skills of readers, institutional decision-makers could be tempted and decide to replace face-to-face courses with these remote practical works, *even under the normal operation* of the education system. Worse, since this paper claims to be written in a pedagogical way and to be self-sufficient, they might as well be tempted to suppress even the presence of the teacher. This hypothesis would be one that turns a good initial idea into a catastrophic end result.

Anyway, even if it is good, especially in research works, to have possible limitations in mind, in particular to foresee in which directions a work can improve or evolve, it remains important to keep its freshness in the first phases of a big job.

### 5.3. Perspectives

Some future research directions are given here, but this list is not exhaustive:

- (i) The first one concerns the *diversity of topics* of the engineering sciences. For example, a power electronics simulator is currently being tested, as well as an electrical motor practical work. A mathematical probabilistic simulator is being also considered.
- (ii) The second research axis deals with the *variation of the modeled data*. For example, concerning the practical work presented in this paper, after having modeled a complete electrical circuit, it could be interesting to propose a continuation of this spreadsheet consisting of varying the frequency and automatically drawing the Bode diagram. Thus, it would become easy to illustrate the effects generated by the different passive components on the frequency response of a circuit. This was not the goal of this first paper, but this axis seems to be interesting, for engineering degrees for example.
- (iii) This work and this file can also be completed for *any other sheet dealing with electronics issues*. For example, for digital or analogical electronic circuits, copy/paste the last module from two to  $n$  times in the cascade assembly, taking into account operational amplifiers, and many other ideas. The possibilities are infinite.

**Supplementary Materials:** The following are available online at <https://www.mdpi.com/article/10.3390/modelling3040029/s1>.

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**Data Availability Statement:** The supplementary material is the Excel file directly available on the MDPI website alongside this paper. All the readers will have the possibility to train on this file, and to improve it the way they deem appropriate for their personal or professional use. A reference to this paper will be greatly appreciated both by the author and the editor of this original and open access research work.

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in the clarification of some notions presented in this paper. Furthermore, the author would like to thank the anonymous Reviewers for adding value to this article through their valuable comments and questions.

**Conflicts of Interest:** The author declares no conflict of interest.

**Sample Availability:** As mentioned in the abstract, the main goal of this paper was **pedagogical**, and is geared to students. Then, the corresponding Excel file **with holes appearing in green color in this paper in Figures 4, 6 and 8** is available alongside the paper, on the MDPI open-access website. Thanks to their careful reading of this paper, they will be able to supplement them advantageously and continue this work in their own directions.

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