
Laboratory work in teaching basic three-phase electrical circuits

Alfonso Bachiller-Soler, Pedro J. Martínez-Lacañina and Darío Monroy-Berjillos
*Department of Electrical Engineering, Escuela Técnica Superior de Ingenieros,
University of Sevilla, Spain*
E-mail: abslhm@us.es

Abstract This paper describes a laboratory-based teaching proposal for the understanding of three-phase circuits at the undergraduate level of engineering degrees. The practical content of the proposed activities is oriented towards easing the students' understanding of the main concepts involved in three-phase circuits. The subject of three-phase circuits forms the basis for an elementary undergraduate course on circuit analysis. This work proposes simple and didactic laboratory lessons for the long-term understanding of many concepts involved in three-phase circuits which are often covered by only theory or simulation. The practical teaching proposed has been successfully implemented in the Industrial School of Engineering of the University of Seville and can easily be included in the laboratory curriculum of other Engineering schools.

Keywords power system engineering education; three-phase circuits; undergraduate laboratory

In Spain, engineering education is evolving to fit the new requirements and to satisfy the new challenges in the forthcoming European Higher Education Area (EHEA).¹ In addition to other formal aspects, one of the key issues of this forthcoming reform has to do with the role of students, frequently reduced to a passive agent facing nearly 30 hours a week of lessons, particularly in countries like Spain where a strong mathematical background is promoted. Although such a theoretical emphasis may allow today's engineers to adapt more easily to future changing environments, this is also believed to be the main source of students' lack of creativity and motivation. Today's engineers must adapt to changing environments, engage in lifelong training to maintain their technical skills and knowledge, work effectively in a team, and have knowledge of the business, societal, and environmental impact of their work.

In the USA, in order to encourage engineering programs to respond to these changes, the Accreditation Board for Engineering and Technology (ABET)² has a set of criteria that engineering programs must satisfy for graduating students in their Engineering Criteria (EC2000).^{3,4} As an example of two of those criteria, EC2000 specifies that graduating students should have an ability to design and conduct experiments, as well as to analyze and interpret data; and an ability to identify, formulate and solve engineering problems. Consequently, the student skills related to the experimental work turns out to be of great relevance.

A major percentage of the recently proposed educational innovations can be classified into the following three groups:

- E-learning applications which allow the student to follow certain subjects without the need for class attendance;

- Software tools aimed at improving the graphical interface and interactivity;
- Lab-based teaching as an essential part of the student teaching-learning process.

This paper is focused on the third group, and the proposed experience responds to the EC2000 criteria regarding the importance of improving the empirical competences. In other words, to successfully develop students with these kinds of knowledge and skills, the fundamentals of electrical engineering will be introduced in the context of application rather than as isolated technical concepts and principles.⁵

Motivation for the laboratory practice

New information and communication technologies have been successfully applied in engineering studies,^{6,7} but direct experience in hands-on lessons provided in real laboratories cannot be omitted and the proper design of such laboratories is of key importance. Furthermore, virtual and real labs can be combined to provide improved performance of subject teaching.^{8,9} Apart from several simulation-based activities proposed within the power engineering field, some lab designs have been proposed for the teaching of electrical machines and drives.^{10,11} Nevertheless, practical teaching methods for concepts related to three-phase systems have yet to be the focus of attention in educational research, in spite of the difficulties in understanding experienced by students in this field.

The fact that key topics for electrical engineers, such as three-phase systems, are not properly assimilated by many students has already been addressed. The traditional methodology based on small group of students gathered around a tutor who acted as a demonstrator exhibited serious deficiencies. It was not learning-centered since, despite offering several learning activities, the nature of such activities did not allow students to actively get involved in them. Knowledge was transmitted but skill acquisition was not guaranteed. Moreover, because students did not learn by acting and observing the results of their own actions but rather by listening to the instructor explain what they had to learn, no effective learning occurred.

This motivated the design of an experimental laboratory at the University of Seville for the in-depth understanding of the main concepts involved in the teaching of three-phase systems. The main goal of the proposed practical teaching is to let the students build the three-phase system and experiment with both balanced and unbalanced circuits. In this way, the student can compare both theoretical and experimental results and thereby approach the research methodology by playing an active role in the centre of the teaching-learning process. The proposed lab and methodology are simple and require no expensive infrastructure, but reinforce the main concepts of three-phase systems with a set of experiments designed so that the student can properly understand the theoretical lessons. This proposal is expected to be useful for educators and for the direct implementation of lab lessons in various engineering degrees. Special emphasis has been placed on practice to facilitate the adaptation of courses to the EHEA context.

Brief background theory

Assume a three-phase circuit with wye connection which is modeled as shown in Fig. 1.

This system is formed by one three-phase voltage source U_{RN} , U_{SN} , U_{TN} , one three-phase load, R_R , R_S , R_T , that has been taken as resistive for the sake of simplicity, and one resistance R_N connected between the load and source neutrals, O and N respectively.

The voltage, U_{ON} , between the load and the source neutrals can be obtained by applying Millman's theorem:¹²

$$U_{ON} = \frac{\frac{U_{RN}}{R_R} + \frac{U_{SN}}{R_S} + \frac{U_{TN}}{R_T}}{\frac{1}{R_R} + \frac{1}{R_S} + \frac{1}{R_T} + \frac{1}{R_N}} \quad (1)$$

Once U_{ON} has been calculated, the load voltages and line currents are

$$U_{RO} = U_{RN} - U_{ON}; \quad I_R = \frac{U_{RO}}{R_R} \quad (2)$$

$$U_{SO} = U_{SN} - U_{ON}; \quad I_S = \frac{U_{SO}}{R_S} \quad (3)$$

$$U_{TO} = U_{TN} - U_{ON}; \quad I_T = \frac{U_{TO}}{R_T} \quad (4)$$

On the other hand, the yielded neutral current is

$$I_N = I_R + I_S + I_T \quad (5)$$

The above analysis is general, and can be applied to the case of a symmetric or non-symmetric source and to a balanced or an unbalanced load. This paper is focused on three-phase systems with symmetric source since they constitute a very useful real application in electric power systems.

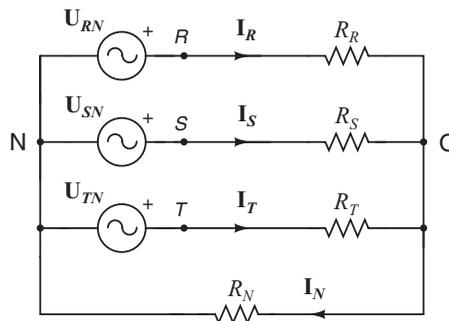


Fig. 1 Three-phase system with wye connection.

A three-phase voltage source is considered symmetric if the following conditions are verified:

$$\mathbf{U}_{RN} + \mathbf{U}_{SN} + \mathbf{U}_{TN} = 0; \quad U_{RN} = U_{SN} = U_{TN} \quad (6)$$

Moreover, eqn (6) implies that the line voltages are symmetric:

$$\mathbf{U}_{RS} + \mathbf{U}_{ST} + \mathbf{U}_{TR} = 0; \quad U_{RS} = U_{ST} = U_{TR} \quad (7)$$

Furthermore, the two groups of voltages, i.e. line voltages and phase voltages, are related by a $\sqrt{3}$ factor:

$$U_{ij} = \sqrt{3} - U_{kn} \quad \text{for } i, j, k = R, S, T \quad \text{with } i \neq j \quad (8)$$

The resistances R_R , R_S and R_T can be changed from zero to a pre-specified value, which enables a three-phase balanced or a three-phase unbalanced system to be achieved.

In order to obtain a balanced system, the following relationship needs to be satisfied:

$$R_R = R_S = R_T \quad (9)$$

In such a situation, $\mathbf{U}_{ON} = 0$ according to (1), and it follows that

$$\mathbf{U}_{RO} = \mathbf{U}_{RN}; \quad \mathbf{U}_{SO} = \mathbf{U}_{SN}; \quad \mathbf{U}_{TO} = \mathbf{U}_{TN} \quad (10)$$

and

$$\begin{aligned} \mathbf{I}_N &= \mathbf{I}_R + \mathbf{I}_S + \mathbf{I}_T = 0 \\ I_R &= I_S = I_T \end{aligned} \quad (11)$$

Note that an important issue is the fact that the neutral impedance is not involved in the problem solution.

Now, the case of an unbalanced system is considered, for which

$$R_R \neq R_S \neq R_T \quad (12)$$

In this situation, the neutral resistance value takes great importance:

If $R_N = 0$ then $\mathbf{U}_{ON} = 0$ and it follows that:

$$\mathbf{U}_{RO} = \mathbf{U}_{RN}; \quad \mathbf{U}_{SO} = \mathbf{U}_{SN}; \quad \mathbf{U}_{TO} = \mathbf{U}_{TN} \quad (13)$$

However, since the load is unbalanced:

$$\begin{aligned} \mathbf{I}_N &= \mathbf{I}_R + \mathbf{I}_S + \mathbf{I}_T \neq 0 \\ I_R &\neq I_S \neq I_T \end{aligned} \quad (14)$$

If $R_N \neq 0$ then $\mathbf{U}_{ON} \neq 0$ and it follows that:

$$\mathbf{U}_{RO} \neq \mathbf{U}_{RN}; \quad \mathbf{U}_{SO} \neq \mathbf{U}_{SN}; \quad \mathbf{U}_{TO} \neq \mathbf{U}_{TN} \quad (15)$$

Consequently

$$I_R \neq I_S \neq I_T \quad (16)$$

If there is no neutral conductor, i.e. $R_N = \infty$, then $\mathbf{I}_N = 0$, otherwise $\mathbf{I}_N \neq 0$.

Physical setting

At first, the metering instrumentation as well as the laboratory and the class organization are presented to students. The physical layout of the laboratory is designed so that students have enough space to arrange tests by themselves. The following equipment and metering instrumentation are used:

- 230/400 V, 50-Hz three-phase a.c. power supply from the 400 V three-phase grid (Fig. 2).
- Bank of variable loads (Fig. 3). Note that for this application only the resistance module will be used. The values of these resistances are controlled by three

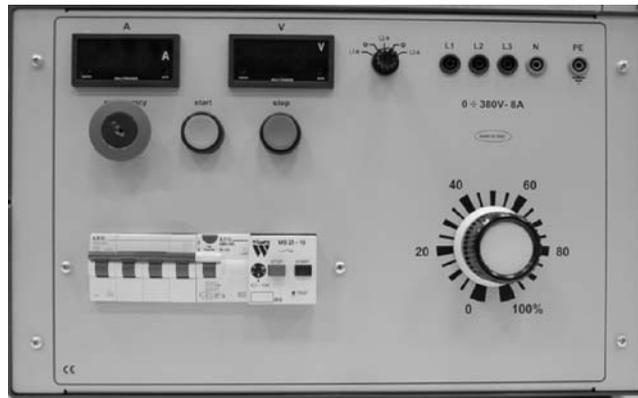


Fig. 2 A.c. three-phase source.

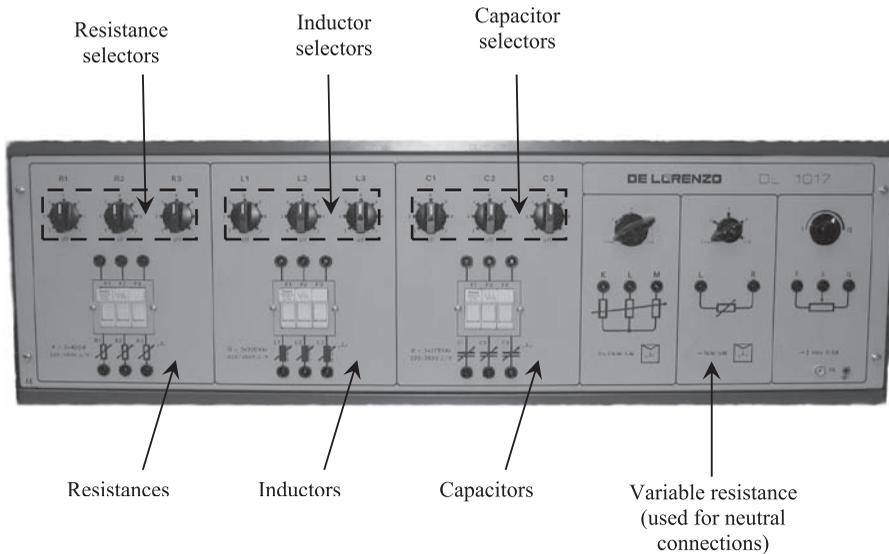
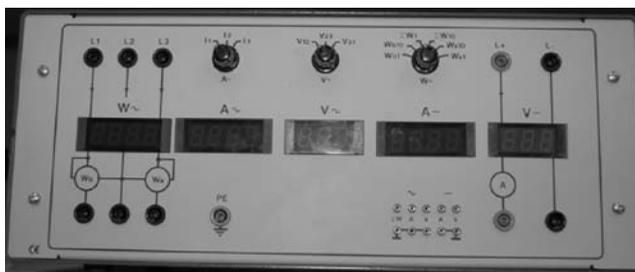


Fig. 3 Bank of variable loads.

TABLE 1 *Resistance values in terms of selector positions*

Selector position	R (Ω)
1	1050
3	435
5	213

Fig. 4 *Three-phase metering instrument.*

selectors as shown in Fig. 3. For the purpose of this paper, the resistance values are shown in terms of the selector positions in Table 1.

- One three-phase metering instrument used to measure the line currents and voltages (Fig. 4).
- Three voltmeters used to measure the phase voltages.
- One voltmeter and one ammeter used to measure the voltage between neutrals, and current that flows through the neutral conductor, respectively.

Laboratory work

The proposed laboratory work consists of a study of the three-phase magnitudes in the particular case of wye connection. The neutral impedance influence is especially emphasized. The experiments allow students to verify the theoretical relations explained in the classroom. Comparing numerical results with theoretical data shows students the limitations of the laboratory work as well as the effect of the simplifying assumptions.

Two hours are allocated to carry out the laboratory work. Typically the students work individually or in two-person teams. Based on our experience of this particular approach over seven years, we think that to make the most of time well spent, each student has to carry out the proposed calculations during the laboratory work process. This forces the instructor to pay special attention not only to the physical implementation but also to the results obtained.

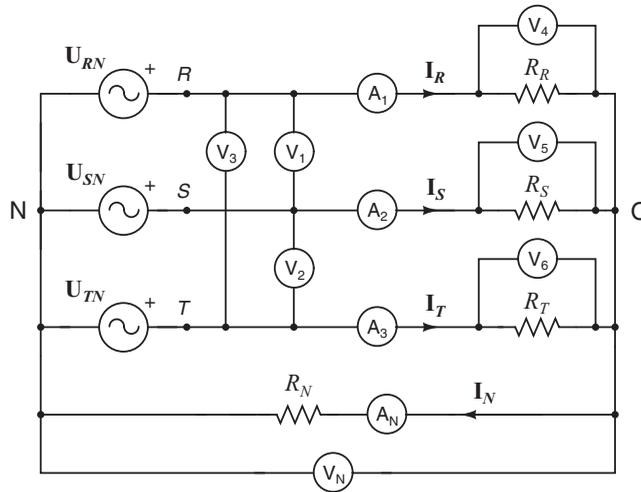


Fig. 5 Three-phase system with wye connection for laboratory work purposes.

The laboratory work comprises the following parts:

- Creation of the three-phase network
- Measurement of proposed magnitudes, i.e. voltages and currents
- Calculation of results of several activities proposed.

Connection diagram

The laboratory work is based on the circuit shown in Fig. 5, which is the same as Fig. 1, but includes the metering equipment.

Students are informed that they must connect up the three-phase circuit by following certain instructions. In the first step the instructor explains how to make the typical wye connection (students have a great difficulty doing this); in the second step the students are invited to complete the current circuit; in the third step the instructor warns about the danger of a bad connection of ammeters and voltmeters. Additionally, a routed diagram is provided (Fig. 6), which is particularly useful for the students. Fig. 7 shows an example taken from a practical session in the Industrial Engineering School of the University of Seville.

Table of measurements

Once the three-phase network has been made, the student can carry out the tests following the indications in Table 2. The first column shows the selector positions for the three-phase resistance. If the three selectors have the same value, i.e. 1-1-1 or 3-3-3, then the corresponding resistances have the same value. The second column indicates the neutral state, i.e. the case of $R_N = 0$, known as the rigid neutral, and the conductor which joins the two neutrals has a negligible resistance; the $R_N = \infty$

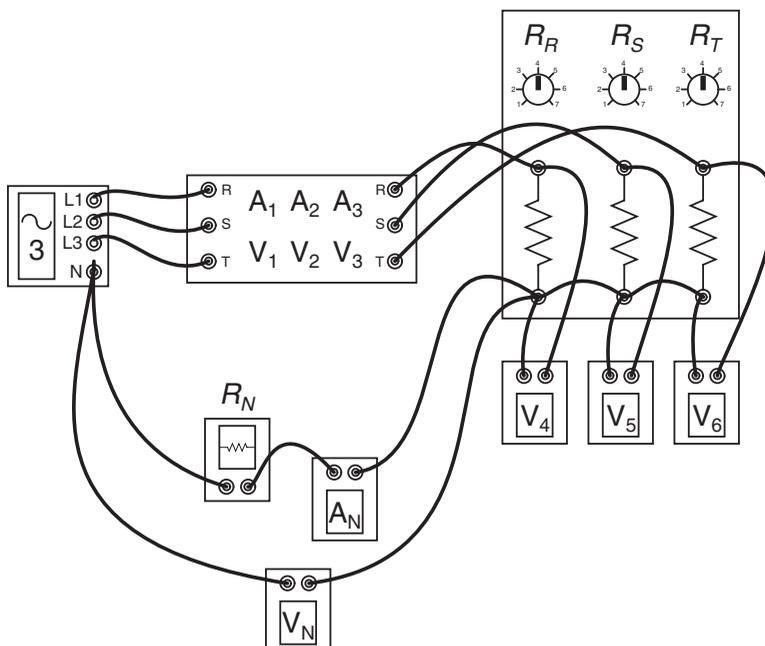


Fig. 6 Routed diagram.

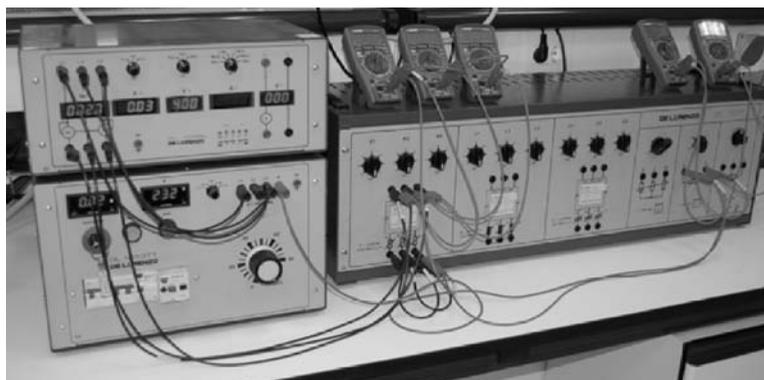


Fig. 7 Three-phase circuit experiment.

case corresponds to the isolated neutral; otherwise the value of R_N is irrelevant (it can be set to an arbitrary value) and it is marked with a (-) symbol. The remaining columns make reference to the corresponding voltmeter and ammeter measurements as shown in Fig. 5.

For each test under consideration, voltage meters ($V_1, V_2, V_3, V_4, V_5, V_6$, and V_N) have to be used in order to measure the line voltages U_{RS}, U_{ST}, U_{TR} , the voltage drop

D

TABLE 2 Test measurements

Selector position	R_N (Ω)	V_1 (V)	V_2 (V)	V_3 (V)	V_4 (V)	V_5 (V)	V_6 (V)	A_1 (A)	A_2 (A)	A_3 (A)	A_N (A)	V_N (V)
1-1-1	–											
3-3-3	–											
1-3-5	0											
1-3-5	∞											

at each resistance U_{RO} , U_{SO} , U_{TO} , and the voltage U_{ON} between the neutrals N and O. In the same way, ammeters (A_1 , A_2 , A_3 , and A_N) must be used for the line current I_1 , I_2 , I_3 , and neutral current I_N measurement. The results are then written down in Table 2 by the students.

Proposed activities

This part is very important because the pupils have to interpret the measurements of Table 2. Furthermore this permits students to connect the theory developed in the classroom with ‘reality’. For this purpose, in the first step the students have to verify a few relations depending on the neutral state, i.e.:

- In the cases when $R_R = R_S = R_T$ (tests 1 and 2 with selector positions of 1-1-1 and 3-3-3, respectively, corresponding to rows one and two of Table 2), relation (8) is verified between the line and phase voltages in the three-phase load. The fact that $A_N = 0$ and $V_N = 0$ is also verified.
- In the case when $R_R \neq R_S \neq R_T$ and $R_N = 0$, then it is verified that relation (8) remains valid in the three-phase load and $A_N \neq 0$.
- In the case when $R_R \neq R_S \neq R_T$ and $R_N \neq 0$, then it is verified that, by properly substitution of the neutral N by O, relation (8) is not valid in the three-phase load and $A_N \neq 0$.

In the second step, students have to answer a few questions for which calculations are required:

- In the case when $R_R = R_S = R_T$, calculate the theoretical value of the measurements of ammeters 1, 2 and 3 (line currents) from the values of the phase resistances (Table 1) corresponding to the selector positions 1-1-1. Write down the results obtained in Table 3 and carry out a comparison with the experimental measurements of Table 2.
- In the case when $R_R \neq R_S \neq R_T$ and $R_N = 0$, calculate the theoretical value of the measurements of ammeters 1, 2, 3 and N (line and neutral currents) from the values of the phase resistances (Table 1) corresponding to the selector positions 1-3-5. Write down the results obtained in Table 3 and carry out a comparison with the experimental measurements of Table 2.
- In the case when $R_R \neq R_S \neq R_T$ and $R_N = \infty$, calculate the theoretical value of the measurements of ammeters 1, 2, 3 (line currents) and the voltage between

TABLE 3 *Theoretical results*

Selector position	R_N (Ω)	R_R (Ω)	R_S (Ω)	R_T (Ω)	A_1) _{theor.} (A)	A_2) _{theor.} (A)	A_3) _{theor.} (A)	A_N) _{theor.} (A)	V_N) _{theor.} (V)
1-1-1	–							0	0
1-3-5	0								0
1-3-5	∞							0	

TABLE 4 *Example test measurements*

Selector position	R_N (Ω)	V_1 (V)	V_2 (V)	V_3 (V)	V_4 (V)	V_5 (V)	V_6 (V)	A_1 (A)	A_2 (A)	A_3 (A)	A_N (A)	V_N (V)
1-1-1	–	400	395	399	232	233	223	0.24	0.24	0.23	0	0
3-3-3	–	400	395	399	232	233	223	0.54	0.55	0.52	0.02	0.2
1-3-5	0	400	395	399	232	233	222	0.24	0.54	1.04	0.7	0
1-3-5	∞	400	395	399	310	261	143	0.31	0.60	0.68	0	90

neutrals N and O (U_{ON}) from the values of the phase resistances (Table 2) corresponding to the selector positions 1-3-5. Write down the results obtained in Table 3 and carry out a comparison with the experimental measurements of Table 2.

Practical example

In this section the results obtained from a practical session developed in the laboratories of the Electrical Engineering Department of the University of Seville are shown. In order to simulate a real circuit, a 400 V three-phase inverse sequence source has been used. This line voltage is the standard value in Spain and is equal to that of other European countries. The three-phase load is the same as described in the ‘physical setting’ section.

The measurements obtained during the practical session are shown in Table 4. For the first three rows it is easy to show that relation (8) between the line voltages (V_1 , V_2 , V_3) and phase voltages (V_4 , V_5 , V_6) is approximately verified. In the same way, this relation is not verified for the fourth row, which corresponds to the case of an unbalanced system with isolated neutral. Note that the rigid neutral (third row) implies that the source phase voltages are equal to line voltages. It should be borne in mind that the source is not completely symmetric, as happens in real cases.

Table 5 can now be completed using the background theory and the test measurements.

In the case when the selector positions are 1-1-1 the theoretical values of the ammeters are obtained by applying Ohm’s law as follows:

TABLE 5 Example theoretical results

Selector position	R_N (Ω)	R_R (Ω)	R_S (Ω)	R_T (Ω)	$A_1)_{\text{theor.}}$ (A)	$A_2)_{\text{theor.}}$ (A)	$A_3)_{\text{theor.}}$ (A)	$A_N)_{\text{theor.}}$ (A)	$V_N)_{\text{theor}}$ (V)
1-1-1	–	1050	1050	1050	0.22	0.22	0.21	0	0
1-3-5	0	1050	435	213	0.22	0.54	1.04	0.7	0
1-3-5	∞	1050	435	213	0.29	0.60	0.67	0	90.3

$$A_1)_{\text{theor.}} = \frac{232}{1050} \approx 0.22 \text{ A}; A_2)_{\text{theor.}} = \frac{233}{1050} \approx 0.22 \text{ A}; A_3)_{\text{theor.}} = \frac{223}{1050} \approx 0.21 \text{ A}$$

The discrepancies observed are mainly due to the temperature variation of the resistance values.

In the case when the selector positions are 1-3-5 and $R_N = 0$, the theoretical values of the ammeters are

$$A_1)_{\text{theor.}} = \frac{232}{1050} \approx 0.22 \text{ A}; A_2)_{\text{theor.}} = \frac{233}{435} \approx 0.54 \text{ A}; A_3)_{\text{theor.}} = \frac{222}{213} \approx 1.04 \text{ A}$$

and the neutral current is calculated by taking into account an inverse sequence three-phase source:

$$\mathbf{I}_N = \mathbf{I}_R + \mathbf{I}_S + \mathbf{I}_T = 0.22 \angle 0^\circ + 0.54 \angle 120^\circ + 1.04 \angle -120^\circ = 0.7 \angle -143^\circ \text{ A}$$

In the case when the selector positions are 1-3-5 and $R_N = \infty$, the voltage between neutrals N and O (U_{ON}) is obtained by applying (1)

$$\begin{aligned} U_{ON} &= \frac{\frac{U_{RN}}{R_R} + \frac{U_{SN}}{R_S} + \frac{U_{TN}}{R_T}}{\frac{1}{R_R} + \frac{1}{R_S} + \frac{1}{R_T} + \frac{1}{R_N}} \\ &= \frac{\frac{232 \angle 0^\circ}{1050} + \frac{233 \angle 120^\circ}{435} + \frac{222 \angle -120^\circ}{213}}{\frac{1}{1050} + \frac{1}{435} + \frac{1}{213}} \approx 90.3 \angle -143^\circ \text{ V} \end{aligned}$$

Once the voltage U_{ON} has been obtained, the line currents are calculated as follows:

$$\mathbf{I}_R = \frac{U_{RN} - U_{ON}}{R_R} = \frac{232 \angle 0^\circ - 90.3 \angle -143^\circ}{1050} \approx 0.29 \angle 10^\circ \text{ A}$$

$$\mathbf{I}_S = \frac{U_{SN} - U_{ON}}{R_S} = \frac{233 \angle 120^\circ - 90.3 \angle -143^\circ}{435} \approx 0.60 \angle 99^\circ \text{ A}$$

$$\mathbf{I}_T = \frac{U_{TN} - U_{ON}}{R_T} = \frac{222 \angle -120^\circ - 90.3 \angle -143^\circ}{213} \approx 0.67 \angle -106^\circ \text{ A}$$

Note that these line currents could be obtained using the measured-phase load voltages and the corresponding resistance.

It is easy to observe the good agreement between the test measurements and the theoretical calculations. When the students arrive to this point of the laboratory work, they have usually reached a good understanding how three-phase circuits with wye connection work.

Educational experience

This laboratory experience has been given for the last three years in a few programs of Electrical Technology of the Technical Engineering curriculum. At the end of the most recent semester the students were interviewed. An anonymous evaluation form for students was prepared to evaluate students' satisfaction and their opinions about the modified course. The questionnaire has six questions based on a six-point Likert-scale, coded as shown in Table 6, which summarizes the main results of the statements asked. The evaluation form was completed by 43 students out of 50 registered students (about 86%).

More than 80% of the students agree or strongly agree with all questions from 1 to 3. Almost 60% of the enrolled students strongly agreed that the present practice is more instructive than others where simulation tools are used. Practically all students think that the practice should be repeated in the next academic courses.

From the detailed analysis of the completed evaluation forms, the adequacy of the proposed practical teaching has been demonstrated to enhance theoretical knowledge and improve experimental skills. Students consider the proposed method as valuable for their education. Although the students' responses have been very positive, their comments also provide useful material for further improvements of the practice and novel methods demonstrated experimentally. It is the belief of the authors that this proposal for experimental activities can be of major use in the

TABLE 6 Evaluation form for students and their responses

No.	Question	Answers (in percentages)				
		SD	D	I	A	SA
1	The practice is well prepared and structured.	0.00	0.00	13.95	53.49	32.56
2	The topics are presented in an appropriate way.	0.00	0.00	18.60	39.53	41.86
3	I find the script helpful for preparation for the exam.	0.00	2.33	23.26	53.49	20.93
4	This practice is more instructive than others where simulation tools are used.	0.00	2.33	11.63	23.26	62.79
5	This practice should be repeated in subsequent years.	0.00	0.00	2.33	41.86	55.81
6	I find the practice relevant for my future profession.	0.00	4.65	23.26	37.21	34.88

Key: SD-Strongly Disagree; D-Disagree; I-Indifferent; A-Agree; SA-Strongly Agree

community of power engineering educators and can be directly included in the curriculum of various Engineering degrees.

Conclusions

Experimental practice in engineering studies with hands-on activities is an irreplaceable tool and must be enhanced according to the Engineering Criteria (EC2000) and the new area of education in Europe (EHEA). Experimental teaching allows not only reinforcement of the theoretical concepts and the acquisition of new skills, but also the improvement of affective dimensions such as the student's motivation.

Training on real measurement equipment is very helpful to test students' theoretical understanding of measuring quantities. During the laboratory class, students develop appropriate familiarity with the measurement system available, including ammeters, voltmeters and wattmeters. They also develop appropriate skills to carry out various connections and to verify the previously calculated circuit relations.

Understanding three-phase circuits has traditionally presented difficulties for the students, thereby proving the insufficiency of theoretical lessons to obtain an in-depth and long-term learning of the main concepts. The implementation of a three-phase network laboratory and the design of specific activities to enhance theoretical teaching has proved to be an efficient way of improving the teaching-learning process at the University of Seville over recent years. Some results have shown that students are more interested in hands-on experiments because of showing real conditions and problems more effectively.

The proposed experimental teaching can be extended to other engineering curricula with minimum effort and infrastructure.

Acknowledgements

The authors would like to acknowledge the financial support of the local government Junta de Andalucía under grant P06-TEP-01882 and the MCYT under grant ENE2007-62997.

References

- 1 R. Shearman, 'Bologna: Engineering the right outcomes', *Int. J. Elect. Enging Educ.*, **44**(4) (2007), 97–100.
- 2 Accreditation Board for Engineering and Technology, <http://www.abet.org>
- 3 J. F. Volkwein, L. R. Lattuca, P. T. Terenzini, L. C. Strauss and J. Sukhbaatar, 'Engineering Change: A Study of the Impact of EC2000', *Int. J. Enging Educ.*, **20**(3) (2004), 318–328.
- 4 AUBURN. <http://www.eng.auburn.edu/admin/planning/criteria.html>
- 5 C. L. Magee, 'Needs and possibilities for engineering education: one industrial/academic perspective', *Int. J. Enging Educ.*, **20**(3) (2004), 341–352.
- 6 B. Szabados, 'Interactive outcome-based assessment using multimedia', *Int. J. Enging Educ.*, **20**(2) (2004), 141–151.
- 7 R. Chompu-Inwai and T. L. Doolen, 'The impact of mobile wireless technology on student attitudes in higher education classrooms', *Int. J. Enging Educ.*, **24**(1) (2008), 14–22.

- 8 A. N. D'Andrea, F. Giannetti, G. Manara, M. Michelini and P. Nepa, 'A virtual educational laboratory for telecommunications engineering', *Int. J. Enging Educ.*, **24**(1) (2008), 144–152.
- 9 R. Malaric, H. Hegedus, D. Cmul and P. Mostarac, 'Electrical measurements student laboratory: Replacing hands-on with remote and virtual experiments', *Int. J. Elect. Enging Educ.*, **45**(4) (2008), 299–309.
- 10 M. Braae, 'A design project for electrical engineering students', *Int. J. Elect. Enging Educ.*, **43**(4) (2006), 288–298.
- 11 A. J. Conejo, J. M. Arroyo and J. A. Mora, 'Electric machine undergraduate lab: a traditional approach with a new technical base', *Int. J. Elect. Enging Educ.*, **44**(1) (2007), 12–22.
- 12 J. Frayle, 'Electromagnetismo y circuitos eléctricos' (McGraw Hill, Madrid, 2005) (in Spanish).