Contribution to the Teaching of Electric Power Quality Through Practical and Extension Activities

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***Abstract*—The importance of power electronics (PE) in society is indisputable, providing comfort and productivity with energy efficiency and the use of alternative power sources. However, with the benefits of PE, there are also challenges to maintaining the quality of electrical energy, affected by the intermittency of renewable sources, the presence of harmonic distortions, fluctuations, and voltage imbalances, among other adverse effects. Thus, teaching concepts about power quality is essential for the training of future electrical engineers, making them able to identify and correct problems that may interfere with the correct functioning of electroelectronic equipment. In this sense, the purpose of this work is to share the actions that have been carried out in the electrical engineering course to complement the teaching on power quality in such a way that they can be used by other educational institutions. Extension activities involving industries and companies in the region are presented, in which power quality data are collected for later analysis and the return of results by students. In addition, a didactic workbench is proposed to carry out experimental activities, where the student can install and observe through a power analyzer the influence of different types of load on voltage and current waveforms and on quality indicators. In this way, students are provided with comprehensive and applied training in this area, seeking to connect theoretical knowledge to real-world situations.**

***Index Terms*—power quality, teaching, didactic workbench, extension activities**

I. Introduction

Power electronics (PE) is an essential area in modern society, allowing the development and application of technologies that benefit us daily. Whether in the generation and distribution of electricity, in the automotive industry or in residential electronic equipment, PE plays a crucial role, providing energy efficiency and environmental sustainability. On the other hand, PE has direct impacts on power quality (PQ), generating voltage and current disturbances that can affect the proper operation of the equipment [1]. Therefore, teaching about power quality should be part of the curriculum of electrical engineering courses, presenting concepts and regulations that can contribute to the identification of problems.

Teaching about power quality initially consists of the theoretical presentation of the phenomena involved, such as steady-state voltage variation, the occurrence of voltage fluctuations or imbalances, the existence of harmonic distortions, among others. However, the assessment of power quality depends on the availability of data on voltages and currents in the installation or electrical network under analysis, which implies the use of dedicated equipment for this purpose (PQ meters).

Therefore, checking the power quality implicitly depends on a practical activity, related to the installation and configuration of the PQ meters, as well as the subsequent extraction and analysis of the collected data. This analysis must be based on the indicators and limits proposed in the regulations and technical guidelines [2], [3], allowing to conclude whether the available electrical energy has adequate quality.

Normally, commercial or industrial consumers are only concerned with the quality of service provided by distributors, related to the availability of electricity in their facilities. However, when economic losses start to occur, due to improper operation or equipment damage, the interest in power quality becomes relevant and electrical parameters are monitored.

In this sense, the purpose of this work is to share practical experiences carried out in the Electrical Engineering course, aimed at improving teaching on power quality. For this, a prepared laboratory environment will be described so that students can carry out measurements safely, observing the influence of different types of load on PQ indicators. Additionally, reports are presented on extension activities that involve the analysis of PQ in local industries and businesses, showing the importance of this type of action for student training and productivity of external agents to teaching intuitions.

II. Theoretical Activities

In the Electrotechnics Department at the Federal Institute of Santa Catarina (IFSC), theoretical knowledge about power quality is taught to students in-person classes in the Electrical Engineering undergraduate course and master's degrees in Electrical Energy Systems. In these courses, the subjects of Energy Quality and Efficiency (60 h) and Electrical Energy Quality (30 h) are offered respectively.

In theoretical classes, information is provided about the causes and consequences of the main power quality phenomena, involving steady-state voltage, current and voltage unbalance, current and voltage harmonics, short-term dips, overvoltage and interruptions, flicker, power factor and frequency

The autors would like to thank the IFSC for the financial support granted through public notices 02/2022/PROPPI and 34/2022/PROPPI.

variation. For these parameters, the indicators, procedures and limits provided in PRODIST-8 [2] and IEEE 519 [3] are used. In addition, criteria for carrying out measurements, technical specifications of some commercial PQ meters (Class S or A) and types and limitations of current probes are presented.

Subsequently, the learning verification is performed through an academic work, in which students receive data from measurements of electrical parameters in commercial and industrial facilities and need to analyze whether the power quality on site is satisfactory or not. In this case, the work performed is part of the extension activity proposed in Section IV, in which after the students find nonconformity in relation to technical recommendations, they must determine causes and possible solutions to the identified power quality problems.

III. Practical Activities

To carry out practical activities on power quality, a teaching workbench was organized for this purpose. The block diagram is shown in Figure 1. The workbench consists of a 7.5 kVA three-phase system, which is powered by a delta-star transformer with a 380 V line voltage on both the primary and secondary sides. A line impedance of 3.52% pu is added to the phase and neutral conductors on the secondary side, with the aim of emulating the cable length impedance of a conventional distribution network. The transformer and line impedance specifications are shown in Table I.

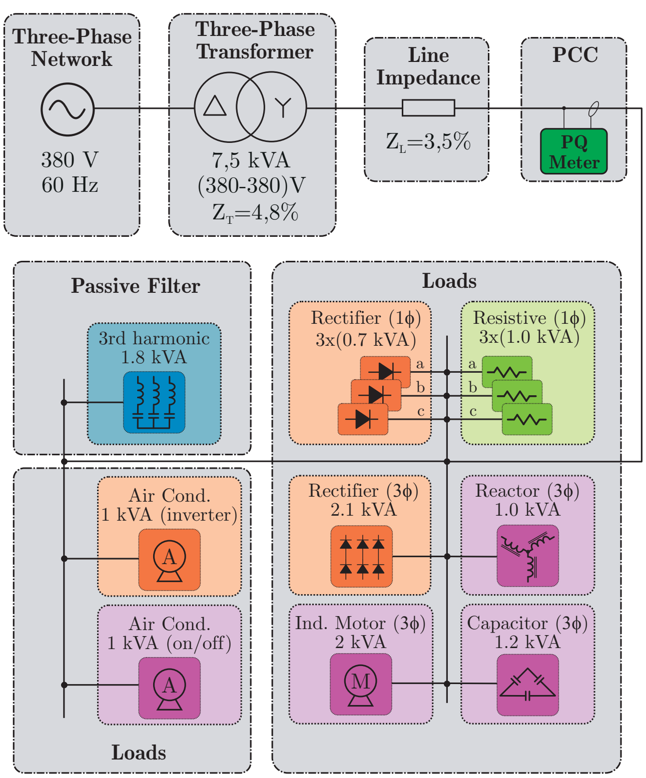


Fig. 1. Didactic workbench block diagram. Different types of linear and nonlinear loads are used to change power quality parameters on the point of common coupling (PCC).

Figure 2 shows the implemented workbench. The proposed use of the didactic workbench is to perform power quality measurements at the point of common connection (PCC), considering the presence of different types of loads. Resistive loads consist of three residential heaters (1 kVA), connected to each phase of the network. Capacitive and inductive loads are implemented using a three-phase reactor (1.0 kVA) and bank capacitor (1.2 kVA) with star and delta connection respectively. The intention is to simulate an inductive displacement factor condition and compensate with capacitive reactive power. All loads can be switched on the control panel.

A. *Rectifiers*

Passive rectifiers with capacitive output filter are used as the main generators of harmonic current components. A three-phase rectifier and three single-phase rectifiers are used, which are implemented with the prototype shown in Figure 3 and with the specifications from the Table II.

TABLE I
Transformer and line impedance specifications.

Parameter	Value
Transformer power	7.5 kVA
Primary coil voltage (V_1)	380 V
Transformation ratio (N_T)	1.7545
Primary resistance (R_1)	1.235 Ω
Primary reactance (X_1)	0.798 Ω
Secondary resistance* (R_2)	0.907 Ω
Secondary reactance* (X_2)	0.798 Ω
Core-loss resistance* (R_c)	3042 Ω
Magnetizing reactance* (X_m)	1174 Ω
Primary side base impedance (Z_1, b)	57.8 Ω
Transformer impedance ($Z_{T,pu}$)	4.83 %
Resistance per conductor (phases and neutral) (R_L)	650 $m\Omega$
Reactance per conductor (phases and neutral) (X_L)	196 $m\Omega$
Secondary side base impedance ($Z_{2,b}$)	19.3 Ω
Line impedance per conductor ($Z_{L,pu}$)	3.52 %

*Parameters referenced to the primary side.

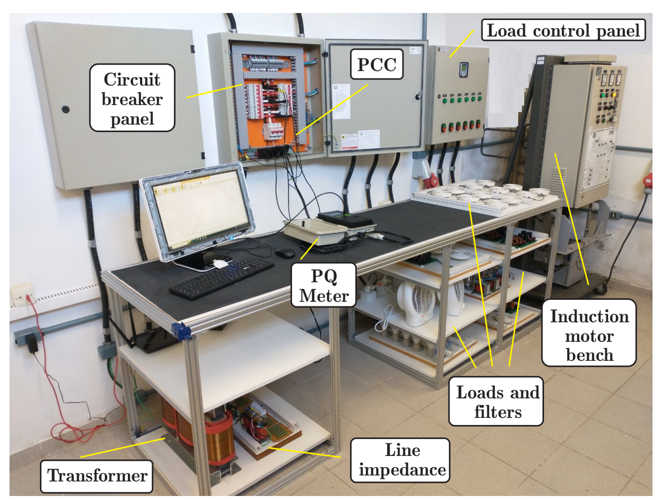


Fig. 2. Image of teaching workbench. A computer is used to visualize in real time the waveforms and other electrical parameters measured by the power quality analyzer.

B. Passive Filter

To demonstrate the possibility of reducing harmonic distortion, a passive filter is implemented to attenuate the 3rd-order harmonic current component. It is considered a shunt-type filtering structure, with inductor and capacitor (in series) connected between phase and neutral conductors.

The passive filter implemented is shown in Figure 4. Inductors and capacitors of 18 mH and 45.5 μF are used respectively, providing a resonance frequency of 176 Hz. This value is slightly below the 3rd harmonic frequency (180 Hz), anticipating a possible loss of filter tuning caused by aging of the capacitors [4], [5]. Due to the resistance of the components, the filter quality factor is around 30.

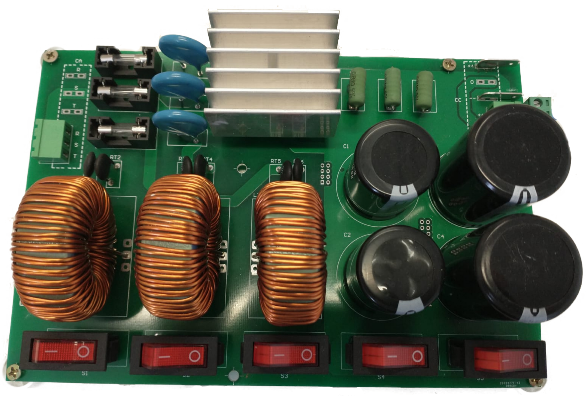


Fig. 3. Diode rectifier prototype. Four PCBs are used, of which three are connected as a single-phase and one as a three-phase rectifier.

TABLE II
RECTIFIER SPECIFICATION.

Parameter	Value
Rectifier bridge model	SDK 25/12 (Semikron)
Input AC inductance	1 mH
Output DC capacitance	400 μF
Heatsink thermal resistance	6.3°C/W
Single-phase power	0.7 kVA
Single-phase power factor	0.66
Three-phase power	2.1 kVA
Three-phase power factor	0.86

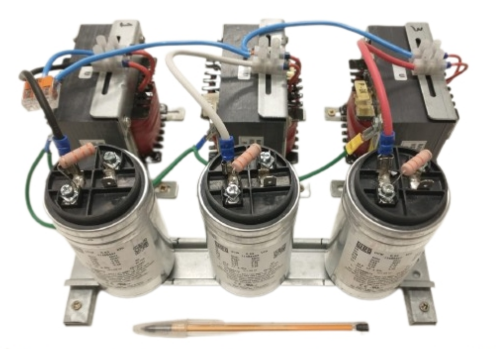


Fig. 4. Passive filter for attenuating the 3rd order harmonic current.

C. Induction motor and air conditioners

It is common to have three-phase induction motors in industrial electrical installations. Due to this, a set of motor drives is connected to the teaching bench, as seen in Figure 2. This set has a 1.5 hp (1.8 kVA) induction motor connected to a magnetic brake. The machine can be activated directly or through an inverter (WEG CFW500). As the inverter model does not have any type of input filter, it is possible to clearly identify the impact of the electronic motor drive on power quality, due to the appearance of current harmonics.

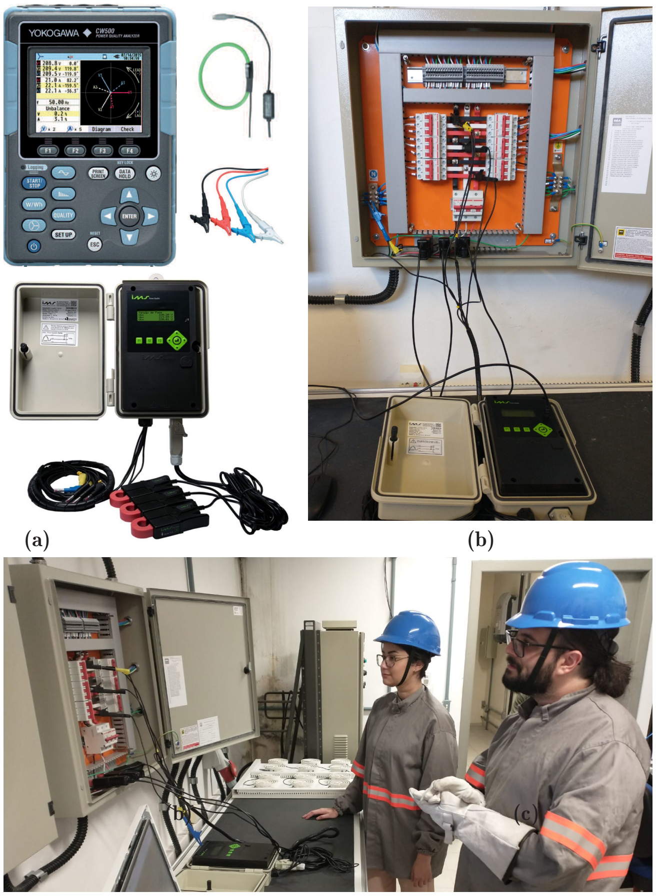
Similarly, the laboratory infrastructure has two air conditioning units, which can be connected to the bench. This equipment is installed in separate rooms of 15 m2 each, one of which is a traditional air conditioner with on/off control (Gree Eco Garden) while the other is an inverter air conditioner (Sansung Wind Free). Both equipment are 12,000 BTU and have a high energy efficiency rating (Class A according to Inmetro/Brazil classification). When the equipment is activated simultaneously, it is possible to verify that the inverter model actually has a significantly lower energy consumption than traditional air conditioning. However, because of the presence of a single phase rectifier, the inverter conditioner contributes to the increase of current harmonics in the power supply network and to the degradation of power quality indicators.

D. Didactic proposal

To carry out practical and extension activities on power quality, the laboratory has two PQ meters, as shown in Figure 5(a). The Yokogawa CW-500 model is used for measurements in industries, having current probes for 1,000 A. For activities on the didactic workbench, the IMS P-600 model is used, with 200 A probes, but which allows measurements with adequate accuracy from 2 A. This equipment allows connection to a computer via USB cable. Using the manufacturer's software, it is possible to view waveforms and power quality indicators in real time. The PQ meter is connected to the PCC, as shown in Figure 5(b).

In practical activities, the teaching proposal is initially to present personal protection items and electrical safety procedures. As shown in Figure 5(c), student volunteers are equipped with clothing, helmet and protective glasses. Considering that the power panel is energized, the student who connects the measuring equipment receives a pair of gloves for electrical contact. Students are instructed to connect voltage and current probes in locations that provide mechanical stability, preventing accidental disconnections from occurring during the measurement period. Furthermore, the care required to avoid phase switching between voltage and current probes is explained, as well as the fact that the direction of the current must be observed to avoid measurement errors.

After the equipment is connected, the power quality parameters are observed on the computer. Initially, steady-state voltage and harmonic distortion values without loads are observed. These values become worse as the loads that generate current harmonics are activated.



(a) (b) (c)

Fig. 5. Use of the didactic workbench.: (a) PQ meters available in the laboratory; (b) Connection of the PQ meter to the PCC; (c) Students connecting equipment and using personal protective items.

Tests are carried out to demonstrate the use of capacitors to correct the displacement factor in the presence of inductive loads (induction motor and reactor). However, it is shown that the use of capacitors does not correct the power factor due to the existence of nonlinear loads. An increase in harmonic distortion is even observed as a result of the occurrence of a parallel resonance between the capacitor bank and the input inductance. It is proposed to exchange the capacitor bank for the third harmonic filter. It is observed that the displacement factor is compensated by the filter capacitors, at the same time that the third-harmonic current is reduced.

Changes in current harmonic content and voltage harmonic distortion in the PCC are observed with the inclusion or removal of rectifiers. In the case of single-phase rectifiers, the presence of third harmonics in the neutral conductor is emphasized. It is shown that due to the linear sum of the zero sequence harmonics in the neutral conductor, the total RMS current is greater than the currents in the phase conductors. The neutral current is reduced by inserting the passive filter.

Another interesting phenomenon is the compensation of the fifth harmonic current produced by single-phase rectifiers through the connection of the three-phase rectifier. The amplitudes of the fifth-harmonic components of the two structures are similar, however, the three-phase rectifier provides harmonics 180° out of phase in relation to the single-phase structure. Therefore, when the three-phase rectifier is connected, it is observed that the fifth harmonic practically disappears from the PCC, which is exchanged between the rectifiers without being requested from the electrical network.

IV. Extension Activities

Extension activities are carried out in industries and local companies, aiming to obtain real data for teaching about power quality, and at the same time contribute to the safety and productivity of these partners. There is a very large demand for these extension activities, either by companies with problems in the operation of their equipment or out of curiosity to know how the quality of energy is at the connection point.

Today, according to Resolution n° 7/MEC/CNE/CES [6], extension activities must comprise at least 10% of the total curricular workload of undergraduate courses. Therefore, taking measurements and producing reports on power quality are opportunities for students to meet the additional requirements of the Electrical Engineering program.

In 2018, a pilot study on power quality was carried out at the IFSC medium voltage substation [7], [8]. The activity served as the basis for defining measurement procedures, which began to be applied in other electrical installations outside the educational institution. At the moment, more than ten companies have already participated in extension activities, normally involving more than one point of analysis.

A. *PQ meter connection*

The extension activity with companies begins with sending a letter of intent. This letter defines the responsibility of the company (access to installations and electrical diagrams) and the educational institution (measuring equipment, data analysis, presentation of results). If the terms of the agreement are accepted, a technical visit is carried out by the project's professors to recognize the electrical installation and identify the measuring point. If safe access to the measuring point is feasible, the PQ meter is installed, which remains in place for up to 15 days. In Figure 6 are some images of the PQ meter connection. After this period, the professors return to the site to disconnect the measuring equipment. Visits to the measurement site are always accompanied by an employee of the company. For safety reasons, no students are involved in the measurement stage. Later, they can return for another technical visit with a lower level of contact with risk locations.

B. *Measurement analysis*

The data collected are downloaded from the measuring equipment and provided to students in power quality subjects. Students also receive information about electrical installation, which is necessary for the application of technical recommendations (as is the case with [3]). Transformer data, conductor gauge and length up to the measurement point, capacitor bank values are provided, among others.

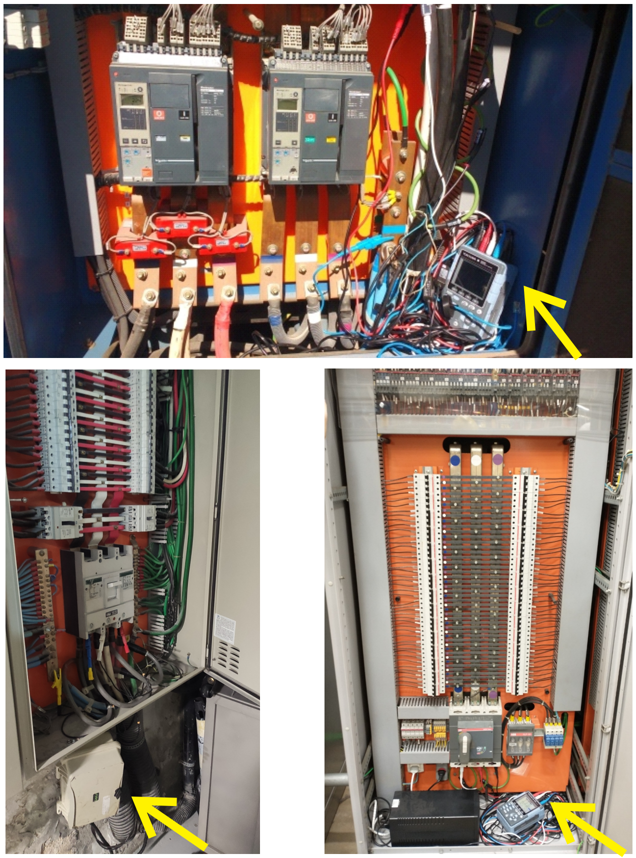


Fig. 6. Connection of PQ meters to companies' main energy panels.

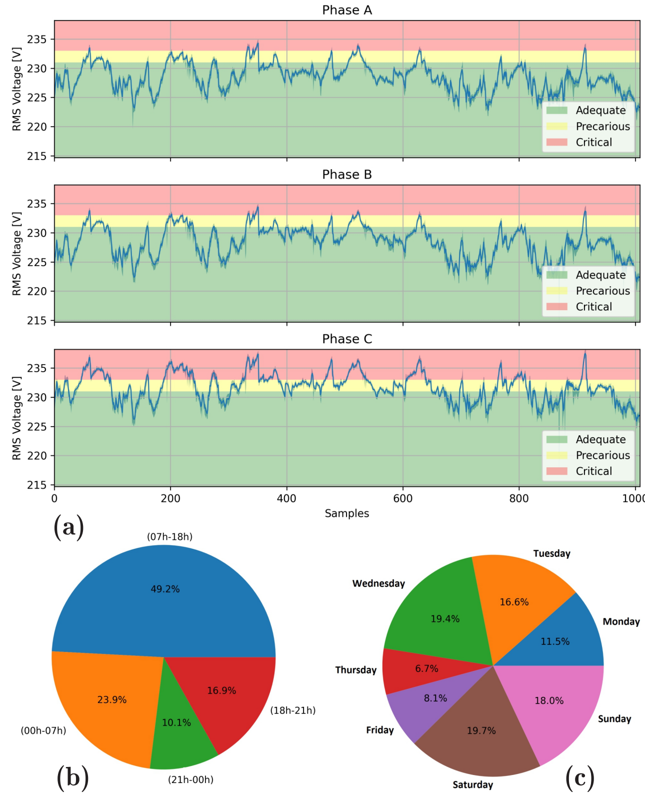


Fig. 7. Example of steady-state voltage recording (a) and distribution of voltage transgressions for the precarious range by time group (b) or week days (c).

The collected data are then analyzed by the students, considering the technical information passed on in theoretical classes. Indicators are extracted and verified in relation to the limits set out in [2], [3]. All power quality parameters mentioned in Section II are considered.

C. Results presentation

After analyzing the data and interpreting the energy quality parameters, the students prepare a report with the results obtained. An example of steady-state voltage is shown in Figure 7. The voltage measurements in the three phases are obtained every ten minutes (according to [2]) and result in Figure 7(a). From this graph, it is possible to identify different voltage transgression situations for precarious and critical value ranges, allowing the DRP and DRC indicators requested by [2] to be calculated. Consequently, the number of transgressions that occur within certain time slots or days of the week is identified (Figures 7(b) and 7(c) respectively).

Results similar to those for steady-state voltage are obtained for other power quality indicators, such as voltage or current imbalances, harmonic distortion, flycker, among others. All results are included in the report, which is sent to the company that participated in the extension activity. In turn, the information provided to the company helps identify those responsible for power quality problems. When possible, a face-to-face presentation of the results is made, allowing the opinion of people who work directly in the maintenance of the companies' electrical installations to be heard. This contributes to the technical training of the students.

V. Conclusions

The activities presented in this work have improved the teaching about power quality at IFSC. It appears that students show greater interest and curiosity in the technical content presented in the subjects.

The practical activities carried out on the didactic workbench demonstrate many of the energy quality problems found in industrial installations. Furthermore, it allows students to take part in carrying out measurements in a more inclusive and safe way (contrary to what would be observed if they went directly to an energy substation, for example).

In the case of extension activities, at the same time as obtaining realistic experimental data to be used in teaching students, valuable technical information is also generated for the owners of electrical installations. This information can be useful in identifying (and avoiding) equipment degradation and problems in industrial production processes. Furthermore, extension activities bring the educational institution closer to the real world, providing students with the opportunity to learn by doing.

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