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Novel Course Design and Assessment of Electrical Engineering Capstone Project*

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With the rapid development and progress of science and technology, in order to help student to meet the everchanging engineering requirements, aiming at the criteria of complex engineering problem solving and continuous improvement established by WA and ABET, this paper proposes a novel course design and assessment method which is applied to the Electrical Engineering (EE) capstone course "Comprehensive Design of Power Electronic Technology" in North China University of Technology. With the introduction of the Hardware in-the-loop simulation phase into the procedure of the capstone course, a "four-dimensional" practical teaching mode including theoretical analysis phase, digital simulation phase, hardware in-the-loop phase and physical experiment phase has been established which allows students to experience more realistic complex engineering problem. And another distinguished feature of the capstone course is the participation of enterprise mentors during the entire designing process. This diversifies the course assessment and consequently a "vectorized" assessment system is accomplished by the participation of group members, course instructors and enterprise mentors. Thus, students' research potential, practical ability and communication & cooperation can be evaluated separately and objectively. On the other hand, a capstone course survey is designed to collect students' feedback from various aspects, and the feedback result analysis and the corresponding course adjustment has been elaborated, thus the continuous improvement of the capstone course is realized.

Keywords: complex engineering problem; continuous improvement; capstone course design; hardware in-the-loop simulation; "vectorized" assessment

1. Introduction

With the rapid development and progress of science and technology, engineering education is continuously evolving to meet new challenges of the emerging technologies and the gradual integration of world economics [1]. In order to maintaining the education qualities, numbers of non-profit engineering education evaluation organizations such as Accreditation Board for Engineering and Technology (ABET) have formulated corresponding standards to evaluate the quality of engineering education in various colleges and universities worldwide. Washington Accord (WA) is an international agreement between bodies responsible for accrediting engineering degree programs [2] which is formulated by ABET and five other international foundation signatory organizations.

Many universities have designed their capstone course according to the WA or ABET's standards, such as complex problem-solving ability. And in addition to imparting professional knowledge related to engineering, students' ability to integrate diverse sets of knowledge and adapt to social changes needs to be further strengthened [3]. Therefore, technological universities in the field of electrical engineering and computer science (EECS) have commenced compulsory capstone courses. Combining theory and practice acquired by students, these types of courses are usually commenced for third and fourth-year university students and are intended to foster students' ability to integrate their own professional knowledge in order to solve practical problems [4]. Capstone design educators should design projects and mentor students to help students promote specific knowledge and skills that students need to independently identify and develop, and help students navigate the design process to complete complex, open-ended projects [5]. An evaluative study at Chongqing Jiaotong University provides a paradigm to evaluate and improve BIM (Building Information Modeling) capstone projects in highway engineering. Results indicate that BIM software training and its theoretical knowledge should be incorporated into BIM capstone courses, BIM coordination meetings in the design process play an important role in capstone course and prior knowledge of teamwork experience has the greatest correlation with performance of capstone joint design [6]. Even though many literatures demonstrated plenty of advanced capstone course designs, the advanced scientific research tools and methods should be introduced more into the capstone course in order to help students to adapt to the requirements of enterprises or graduate studies.

On the other hand, due to the variety processes and complex characteristics of the capstone course,

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the assessment of capstone course is important not only to satisfy ABET's requirement but also to be fair and objective to all participants. And an advanced assessment system will also improve the effect of continuous improvement which is an important benchmark of the engineering accreditation. Based on the above consensus, many researchers contributed in improving the capstone course assessment system. Friess presented an assessment system is capable of assessing individual contributions in a capstone team project, facilitates team formation and operation by requiring continuous team internal feedback, and generates a transparent grading system where students know at all times where they stand [7]. New Jersey Institute of Technology proposed an assessment method used in drone capstone course to examine students' gains in skills and knowledge and attitudes towards an active learning-based approach, it included direct formative (FAA quizzes and programming assignments), direct summative (capstone project), indirect quantitative (survey of learning gains), and indirect qualitative (focus group interviews and capstone project process videos) tools [8]. Linköping University's assessment results of software engineering course indicated that numeric grading was considered to be very important as an incentive to work hard in the course and grading criteria also strongly influenced their way of working [9]. The Ohio State University College of Pharmacy set eleven learning activities including 20 assessments in a capstone course. Each assessment was pass/fail, and students had to pass 15 of 20 assessments to pass the capstone course [10]. Even though there are plenty assessments mentioned above, the participants of assessment are either course instructors or students which are is not diversified enough.

National Taipei University of Technology's research results show that industry-oriented capstone courses are more conducive to the employability performance of the students. They could help students understand the real situation of the industry, and training students to truly connect knowledge and skills [11]. Hence, it is necessary to add the guidance of enterprise mentor into the capstone design. A study from department of Mechanical Engineering University of British Columbia's finds that the participation of design mentors can reinforce relevance in the projects and ensure that practices parallel those of industry. Having the industry engaged in the education process strengthens the overall learning experience for the students [12]. Sha from the University of Houston-Clear Lake introduced the experience of Industry mentors work together with Instructors of Capstone project course to guide the Capstone teams to complete a team-long project beginning from requirement analysis [13]. And comparing to the existing literature, the enterprise mentor has a clearly potential to play a more important role in the capstone course.

Another important factor in the WA or ABET's standards is the continuous improvement. Many literature elaborated different kinds of methods in order to achieve continuous improvement of the courses. McMaster University proposed the Q-methodology to investigate patterns of thoughts within a group and to offer greater potential for the pathoanatomy course reform [14]. A case study in Sichuan Vocational Colleges of Cultural Industries English teaching course is illustrated based on the quantitative analysis of course objective achievement in order to implement a closed-loop of continuous improvement [15]. Shanghai Normal University utilized the hybrid teaching method including integrating high-quality online and offline teaching resources, adopting a variety of digital enhanced teaching methods, and reconstructing the teaching process of on-site courses in order to improve the teaching quality of the C language programming course [16]. However, since the enterprise mentor plays an important role and the "vectorized" assessment system is utilized in our capstone course design, the method to realize continuous improvement based on these specific situations need to be further developed.

No matter WA or ABET's own standard such as Engineering Accreditation Commission (EAC), solving complex engineering problems and continuous improvement are two important benchmarks for evaluating the engineering education qualities. In order to meet those criteria, this paper proposes a novel course design and assessment method which is applied to the Electrical Engineering (EE) capstone course "Comprehensive Design of Power Electronic Technology" in North China University of Technology. Section 2 discusses the "four-dimensional" practical teaching mode and the two distinguished features of the capstone course design which are the hardware in-the-loop (HIL) simulation and the participation of enterprise mentors. Section 3 illustrates the four phases of the capstone course in detail which including theoretical analysis, numerical simulation, hardware in-the-loop simulation, and physical experiment phase. Section 4 introduces the "vectorized" assessment system of the capstone course which is composed by group members, course instructors, and enterprise mentors evaluations. Section 5 indicates the students' feedback about the novel capstone course design and the "vectorized" assessment system and the corresponding course adjustment has been elaborated.

2. Capstone Course Design

Due to the comprehensiveness and flexibleness characteristics of the capstone course, it is an excellent carrier to cultivate students' ability to solve complex engineering problems. Hence, a appropriate capstone course design could accord with most criteria of the complex engineering problems. The definition of the complex engineering problems includes one or more of the following characteristics: involving wide-ranging or conflicting technical issues, having no obvious solution, addressing problems not encompassed by current standards and codes, involving diverse groups of stakeholders, including many component parts or sub-problems, involving multiple disciplines, or having significant consequences in a range of contexts [17]. Traditionally students should experience three phases in a capstone course which including theoretical analysis phase, digital simulation phase and physical experiment phase. First, in the theoretical analysis phase, students should carry out scheme design, topology design and theoretical calculation based on the knowledge of calculus, circuit, power electronics and control theory etc. Then, in the digital simulation phase, students should adhere to the simulation principle and utilize modern simulation tools to complete the digital simulation of circuit topology and verify the theoretical calculation result which have been accomplished in the theoretical analysis phase. Finally, in the physical experiment phase, students should complete the experiment not only including data measurement and waveform interception but also including data processing and waveform analysis, and clarify the reason of the difference between the theoretical circuit and the actual circuit. However, most engineering major course experiments and capstone course cannot reflect the actual application scenarios by the reason of the actual engineering application are always accompanied by extreme conditions such as high temperature, high pressure and high voltage etc. The experiment design has to tradeoff between the reality and safety and develop some expedients such as reducing the voltage and current amplitude of the circuit. And these expedients somehow deviated the practical purpose of the experiment. An element in a circuit performs utterly different by the condition of 50 volts and 220 volts. If the actual application of a certain device is intentionally operating under 220 volts or more, letting students understand the circuit performance in 50 volts is not totally eligible. As shown in Fig. 1, something is missing between the digital simulation phase and the physical experiment phase. Hence, in order to deal with this conflict, additional phase should be added into the traditional capstone course procedure urgently.

2.1 "Four-Dimensional" Capstone Course Practical Teaching Mode

The design goal of the capstone course "Comprehensive Design of Power Electronic Technology" is an single phase AC-DC-AC converter which is simulating the Uninterruptible Power Supply (UPS) which is an electronic power device that delivers voltage to critical loads and whose application must satisfy standardized performance requirements especially for key equipment when power failure occurs [18]. The design voltage of a UPS is 220 volts and it is much higher than the safe voltage accepted by human beings. Hence, for personnel safety, equipment safety, maintenance cost concerns, in order to provide better verification from the theoretical analysis phase to the physical experiment phase, more sophisticated and reliable verification method should be considered despite a digital simulation phase is already on track. In the case of "Comprehensive Design of Power Electronic Technology" which is a typical electrical engineering capstone course, a Hardware in-the-loop (HIL) simulation phase is inserted between the digital simulation phase and the physical experiment phase as shown in Fig. 2.

Nowadays, the Hardware in-the-loop (HIL) simulation technology is widely utilized for scientific research and product design in order to shorten development period and improve research safety and efficiency. Providing such opportunity of utilizing the advanced scientific research tools for stu-

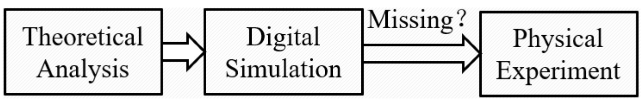

Fig. 1. The three phases of traditional capstone course.

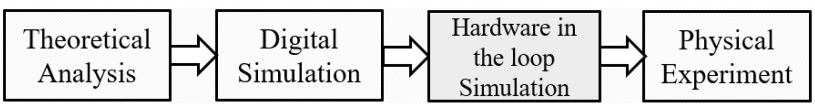

Fig. 2. "Four-Dimensional" capstone course practical teaching mode.

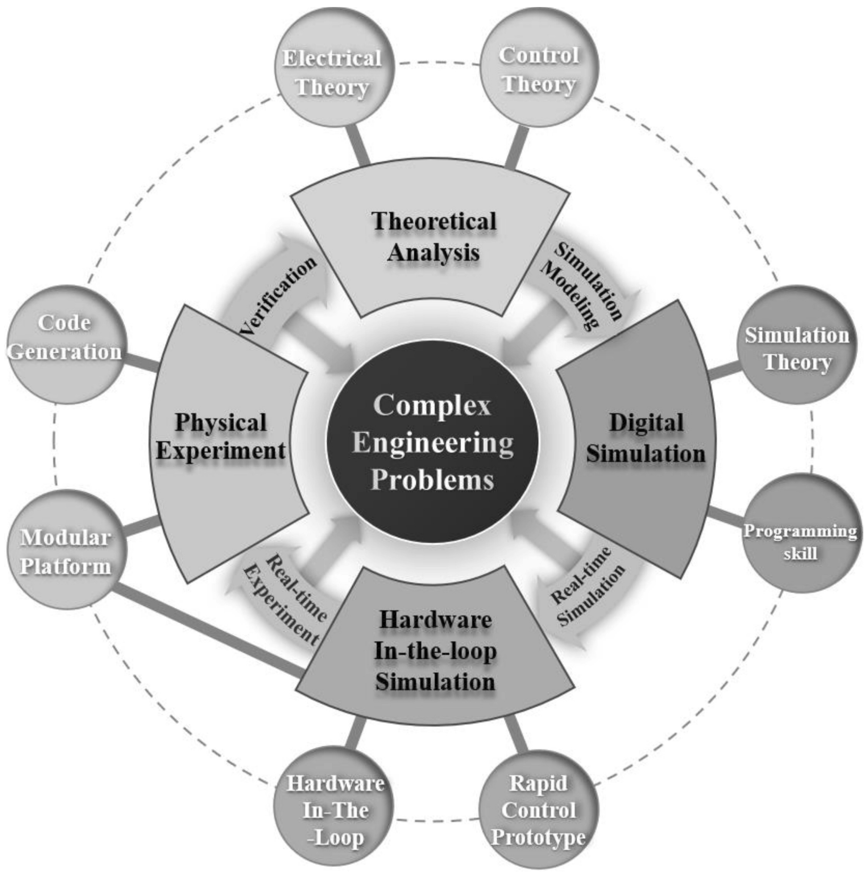

Fig. 3. The relationship among the four phases of the "Four-Dimensional" practical teaching mode.

dents would improve their engineering abilities and help them to adapt to the requirements of enterprises or graduate studies. After inserting the HIL simulation phase, the "Four-dimensional" capstone course practical teaching mode is accomplished and the relationship among the four phases is shown in Fig. 3.

The engineering design concept defined by the ABET includes the following aspects: identifying opportunities, developing requirements, performing analysis and synthesis, generating multiple solutions, evaluating solutions against requirements, considering risks, and making trade-offs, for the purpose of obtaining a high-quality solution under the given circumstances [17]. And the engineering design meets the above requirements can obviously be considered as a complex engineering problem. The requirement of each phase and the connection between different phases are discussed below:

Theoretical analysis phase: Students should analyze and generate multiple solutions to fulfill the deign goals based on the electrical theory and control theory; demonstrate the most feasible scheme against the design requirements; conduct mathematical derivation and modeling based on calculus and complex function knowledge.

Digital simulation phase: Even though a mathematical model is established via the first phase, this mathematical model cannot be simulated by digital computer directly. Hence, a simulation modelling process should be implemented. In this phase, students should transfer the mathematical model into a simulation model which can be simulated by specified simulation software based on the simulation theory knowledge and programming skills.

Hardware in-the-loop (HIL) simulation phase: Due to the characteristics of power electronics such as high voltage and current, the fear of component failure and safety concern have always been a critical problem when students intend to design, control and test power converters. In this phase, by the advantage of the HIL simulator including real-time based rapid control prototyping technology, students are allowed to validate the control strategy design without worrying about the possibility of damaging the semiconductor devices and passive components.

Physical experiment phase: After the validation of the scheme design and control strategy through the HIL simulation phase, a physical experiment which restoring the actual engineering application scenario via a modularized power electronic practical platform can be provided to the students without the trade-off consideration between the safety and reality. And finally a comparison and verification between the experimental data and the theoretical data can be executed.

Through the four different phases of this capstone course, the "Theoretical analysis – Numerical Simulation – Hardware in-the-loop simulation – Physical experiment" practical teaching mode is completed. Students should experience a complete engineering design closed-loop and the ability of solving complex engineering problems is cultivated.

2.2 Hardware in-the-loop Simulation

Since the HIL simulation phase is distinguished feature of this novel practical teaching mode, the detail of this phase will be elaborated in this section. Due to the high-voltage characteristics of electrical engineering research objects, it is impossible to perform experiments on the actual devices for safety and economic reasons. Furthermore, the need for testing and prototyping designs under more realistic conditions is increasing rapidly. Hardware-in-the-Loop (HIL) allows real and virtual components of a system to be tested together, making it possible to perform tests under more realistic conditions without harming the real system [25, 26]. There are many electrical engineering research fields of application that use HIL simulations in order to shorten the development process such as solar photovoltaic [21], wind power generation system [22], microgrid [23] and electric vehicles [24]. In order to keep up with the development trend of electrical engineering and improve students' competitiveness, the HIL simulation is applied between the digital simulation part and physical experiment part of the capstone design. This enables students to design, control, and test power converters without the fear of component failure [25]. Thus, students could experience the latest electrical engineering product development technology.

There are two different technical routes of the HIL simulation application. One route is to combine the HIL simulator as the virtual controller with the physical power electronics modules, the other route is to combine the physical controller with the HIL simulator as the virtual power electronics converters. In our capstone design, both technical routes are implemented.

Virtual Controller – Physical Circuit: A virtual controller is connected to a physical power electronics converter as shown in Fig. 4. The virtual controller is simulated by the HIL simulator utilizing the real-time based rapid control prototyping technology. And the physical power electronics converter which is the AC-DC-AC converter is assembled by the modularized power electronics platform. Students could use the graphical programming software MATLAB/SIMULINK to

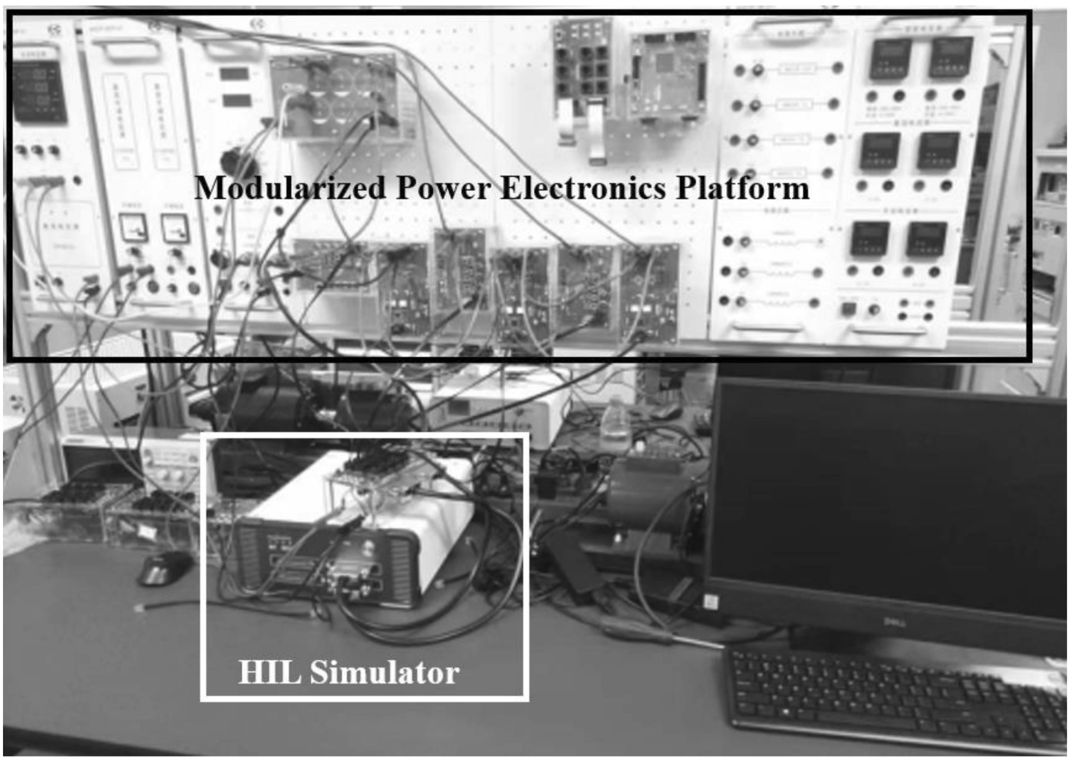

Fig. 4. The HIL simulator (virtual controller) and modularized power electronics platform (physical circuit).

develop the control strategy model and directly load the simulation model into the HIL. Hence, the physical DSP controller is replaced by the HIL simulator. This kind of virtual and physical combined topology helps students to avoid text-based programming and debugging such as C,C++ and VHDL, and shorten the development and verification period of the control strategy design. In this experimental process, the input voltage is set relatively low to prevent physical circuit damage due to control strategy failure.

Physical Controller – Virtual Circuit: A physical DSP controller is connected to a virtual power electronics converter as shown in Fig. 5. In this case, the virtual power electronics converter is simulated by the HIL simulator utilizing the real-time based rapid control prototyping technology. And the physical DSP controller is the control module. Students could use the graphical programming software MATLAB/SIMULINK to develop the power electronics converter model and directly load the simulation model into the HIL simulator. Thus the physical power electronics converter is replaced by the HIL simulator. This kind of virtual and physical combined topology enables students transfer the verified control strategy into the DSP controller via the text-based programming language without the concern of hardware failure since the power electronics converter is virtualized by the HIL simulator. Although the technology of programming DSP controller with graphical programming software such as MATLAB, PSIM is sophisticated enough, it is more important and better for students to understand lower programming mechanism in their learning stage.

After conducting two different HIL simulation based experiments, the control strategy and the power electronics topology design are verified thoroughly. Hence, student should have sufficient confidence to perform the physical experiment despite the discouraging and prohibitive characteristics of the power electronics technology.

2.3 Participation of Enterprise Mentors

With the rapid changes of the times and technological advancement, a gap has appeared between the knowledge imparted by the academic community and the skills needed by industry, resulting in the so-called education–job mismatch [11]. In order to reduce this education–job mismatch, introducing the in-service electrical engineers into the capstone course could be a well-targeted method. In this capstone course design, we keep a long-term teaching cooperation with electrical engineers who work in the electrical engineering field enterprises. These in-service electrical engineers are participating in the capstone course as enterprise mentors. Comparing to the course instructors, the enterprise mentors have the following three aspects of unique advantages:

(1) Abundant Experience of Engineering Projects: According to the general job description of course instructors (university teachers), their primary tasks are teaching and scientific research, besides these two tasks, if they still have the time and

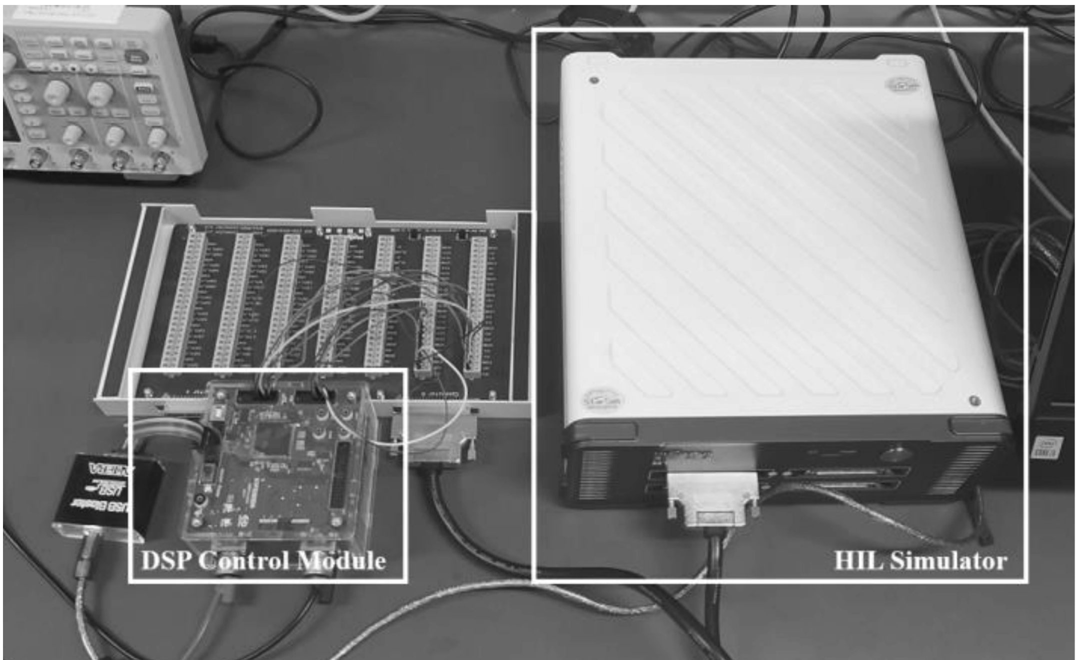

Fig. 5. The HIL simulator (virtual circuit) and the DPS control module (physical controller).

energy, doing engineering projects may eventually become an option. On the contrary, enterprise mentors' daily work is making efforts to meet the engineering design requirements which are proposed by enterprises. They invested much more time in the engineering projects than course instructors which leads to more experience on it.

(2) Focusing on Engineering Application: The methodology of enterprise mentors intends to be more problem oriented since they have to solve problems in order to achieve certain practical engineering application designing goals. Conversely, course instructors pay more attention to the theoretical analysis and mathematical calculations rather than practical engineering application. And most of the time, the theory and the reality do not match perfectly and the aid from both aspects are equally needed. Hence, the combination of enterprise mentors and course instructors would complement with each other effectively.

(3) Better Understanding on the Industry Development Trend: Course instructors tend to pay more attention to the frontiers of scientific research fields, and the latest research achievement is always far from commercial engineering applications. Furthermore, a large proportion of scientific research achievements eventually will not turn into the practical applications at all. Hence, a competent course instructor may know well in his/her research field, but probably is not familiar with the current industry application and development trend of it. On the other hand, enterprise mentors deal with the current mainstream engineering application as a living, they may not understand the profound theory of the relative research field. but as important participation of the industry, they definitely have clearer perspectives of the industry development status and trend.

Based on these unique advantages of enterprise mentors, introducing them into the process of the capstone design course would shorten the distance between students and the practical engineering applications, help students to gain a intuitive and clear view of the engineer's work contents and broaden students' horizons by informing the current situation and prospects of industry development. Hence, we committed to introducing enterprise mentors into the whole capstone course process and making them play an important role in it. The enterprise mentors from power electronics research and development companies are invited to participate in every phases of the design process which will be discussed elaborately in Section 3. Furthermore, with the participation of enterprise mentors, the course assessment is expected to be more pluralistic and stereoscopic which will be discussed in Section 4.

3. The Procedure of Capstone Course

A defining characteristic of professional engineering is the ability to work with complexity and uncertainty, since no real engineering project or assignment is exactly the same as any other [2]. Accordingly, cultivating students' ability to solve complex engineering problems is extremely important for each engineering major. In the case of electrical engineering major, the power electronics technology is the indispensable part of the curriculum system. The actuator of each power converter, motor control system and power system is relied on the power electronics technology. On the other hand, the teaching of power electronics is plagued by some key issues and challenges. The first and foremost problem commonly encountered is that power electronics courses often start with equation derivations, mathematical analysis, memorization, and highly theoretical lectures that fail to engage students [26]. Furthermore, the high voltage and current characteristics bring challenges to students in their practical study. Hence, in order to improve the core electrical engineering ability and cultivate the complex engineering problem solving ability of students, the capstone course procedure design can be divided into four phases: theoretical analysis, digital simulation; hardware in-the-loop simulation and physical experiment as shown in Fig. 6.

After one semester's training (16 weeks), students would experience a complete process of electrical engineering design. Since tough times make tough designers, the design task is challenging and perplexing in order to shape engineers' knowledge and identity [27]. The attributes of complex engineering problems [28] in this design task can be reflected as below: (In order to effectively represent the relationship between each attribute of complex engineering problem and the detailed design requirements, each attribute of complex engineering problem is given an abbreviation in parentheses.)

Depth of Knowledge Requirement (CEPA-1): Cannot be resolved without in-depth engineering knowledge which means completing the design task needs to involve most of the core major courses knowledge such as power electronics, control system, circuit, simulation technology etc.

Range of Conflicting Requirements (CEPA-2): The design process involves wide-ranging and conflicting technical, engineering and other issues such as the differences among the mathematical model, simulation model, HIL model and physical model.

Depth of Analysis Required (CEPA-3): Have no obvious solution and require abstract thinking and originality in analysis to formulate suitable models. In the design task, there are no standard solutions in either part of the design task. Each part of design

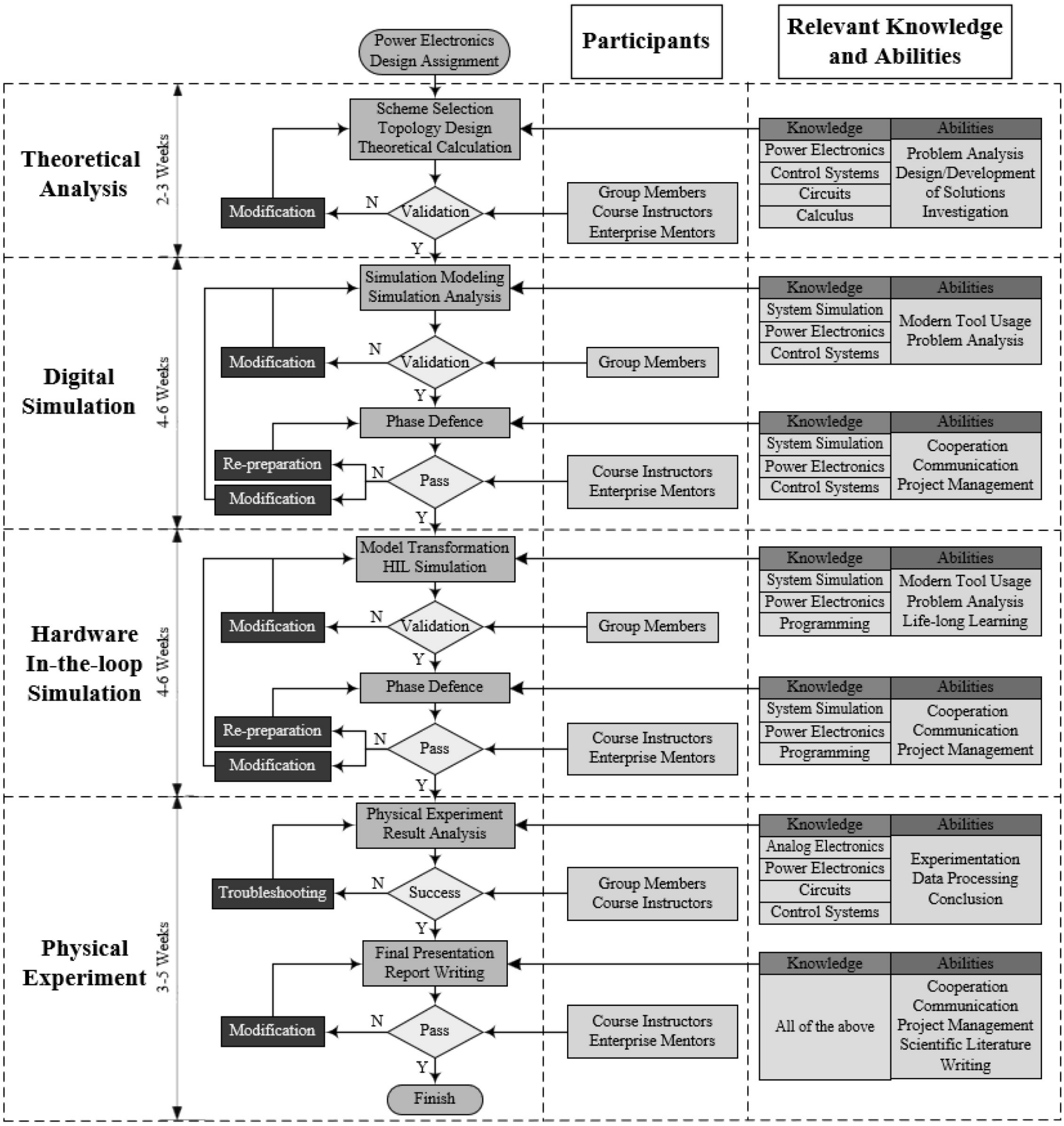

Fig. 6. Procedure of Capstone course "Comprehensive Design of Power Electronics".

requires different modeling and analyzing method such as theoretical modeling, simulation modeling and physical modelling.

Familiarity of Issues (CEPA-4): The design task involves infrequently encountered issues such as hardware in-the-loop simulation research method, real-time based rapid control prototyping technology and PCB hardware circuit design.

Extent of Applicable Codes (CEPA-5): Outside problems encompassed by standards and codes of practice for professional engineering. The communication and cooperation abilities are widely needed since this capstone course is completed by groups and a standard technical report, two periodical defenses and a final presentation are required.

Interdependence (CEPA-6): High level problems including many component parts or sub-problems. The design task includes many component parts and sub-problems such as power electronic circuit topology design, theoretical analysis, simulation modeling, hardware in-the-loop simulation and physical experiment etc.

The detailed design tasks in each phase of the capstone course are summarized into 3–4 parts and the correspondence between the attributes of complex engineering problems and the detailed design tasks is indicated in Table 1. It is worth noting that each design task only corresponds to the most two consistent CEPAs in this table, which does not mean that this design task is not related to the other CEPAs at all. For instance, the design task "Topology Design" is focusing on the determination the power electronics converter topology. This process requires students' depth of knowledge (CEPA-1) and the ability of dealing with conflict situations (CEPA-2) since students have to come out different topologies and compare with each other in order to determine the optimized solution. The ability of coming out different topologies requires the depth of engineering knowledge such as power electronics, circuit and analog electronic technology etc. And determining the optimized solution requires students to make trade-offs in various conflicting technical and engineering issues. However, students are supposed to complete this task in group, and they have to communicate and cooperate with their teammates in the whole process which means it is also related to the less relevant attribute of complex engineering problem CEPA-5.

In this section, the procedure of the capstone course "Comprehensive Design of Power Electronics" will be discussed in detail including the theoretical analysis phase, digital simulation phase, hardware in-the-loop simulation phase and physical experiment phase. The discussion focuses on highlighting the correspondence between each phase and the complex engineering problem attributes. Furthermore, the importance of the novel HIL simulation phase and the participation of enterprise mentors are also emphasized.

3.1 Theoretical Analysis Phase

The design goal of the capstone course is a UPS power electronic converter. And the design constraint includes the input voltage, output voltage, the range of power transmission and the possible load disturbance of the converter. After students understand the design goal, they are required to form a three-student group voluntarily. The grouping is essentially important since the requirement of the capstone course is multifarious including rigorous theoretical derivation, scheme demonstration, detailed mathematical modeling and simulation, experiment, hardware debugging, presentation and scientific literature writing. Setting up a group with balanced abilities will improve the efficiency and quality of completing the design goal.

The duration of the theoretical analysis phase is approximately 2–3 weeks. Firstly, students need to demonstrate feasible schemes which can achieve the UPS function base on the power electronics and circuit knowledge. Secondly, students have to design the topology of the power electronics converter and calculate the parameters of the main circuit components such as filter capacitor and inductor. Thirdly, after confirming the parameters of the converter, the mathematical model of controlled object which is the power electronic converter should be derived accurately through the knowledge of power electronics, differential equations, and circuits. With the self-unstable controlled object, in order to achieve great close-loop control effect, a PI controller should be designed based on the control system theory. In this design stage, the

Table 1. Correspondence between the attributes of complex engineering problems and the detailed design tasks

Phase	Detailed Design Tasks	CEPA-1	CEPA-2	CEPA-3	CEPA-4	CEPA-5	CEPA-6
Theoretical Analysis	Scheme Selection		√	√			
	Topology Design	√	√				
	Theoretical Calculation	√		√			
Digital Simulation	Simulation Modeling	√					√
	Simulation Analysis	√		√			
	Phase Defence					√	√
Hardware In-the-loop Simulation	Model Transformation		√		√		
	HIL Simulation			√	√		
	Phase Defence					√	√
Physical Experiment	Physical Experiment				√		√
	Result Analysis		√	√			
	Final Presentation					√	√
	Report Writing					√	√

contradiction between stability and swiftness is highlighted incisively and vividly. A large filter capacitor could result in the outstanding stability performance of the converter and the voltage ripple caused by the diode rectifier bridge is reduced immensely. However, large capacitor means large inertia of the system, the swiftness of the converter is limited and larger capacitor design also increases the physical size of the converter. Students have to perform tradeoffs between these conflict conditions such as stability, swiftness, ripple reduction and physical size etc. This is a good chance to help students to understand that there is no standard answer in the real practical engineering design, each solution suits a specific requirement. Dealing with various mutually restrictive factors is one of the keys of solving complex engineering problems.

As shown in Fig. 6, in the theoretical analysis phase, group members play the most important role, they have to discuss and come out a full set of solutions including the power electronic converter topology, selections of the components and the parameters of the controller. During this process, students' abilities of problem analyzing, design/development of solutions and investigation are comprehensively trained. Course instructors and enterprise mentors would evaluate the feasibility of the proposed solutions by each group from the perspective of theory and engineering application. If they find out the solution is deficient in either aspect, a modification of the solution is required to proceed into the next phase.

3.2 Digital Simulation Phase

The duration of the digital simulation phase is approximately 4–6 weeks. Based on the approved solution from the previous phase, students are required to transfer the mathematical model of the power electronic converter into a simulation model via the graphic-based programming software MATLAB/SIMULINK in the digital simulation phase. The simulation modelling of a AC-DC-AC converter can be divided into three parts which are AC-DC rectifier simulation, DC-AC inverter simulation and the combination of those two simulations. During this process, students could encounter various kinds of problems such as the programming failure, the huge difference between the theoretical analysis and the actual simulation results and the mistaken analysis of the simulation waveforms and results etc. Groups are expected to struggle with failures and have to cooperation and communicate with each other the whole time until an acceptable simulation result and analysis report is completed. As shown in Fig. 6, at this point, the validation and the modification are all up to the group members. If all the group members decide that their work is mature enough to accept a phase defence, course instructors and enterprise mentors should walk on the stage to challenge their students. And there are three possibilities of the phase defence, if the group performs well in both presentation and technical question answering, they can proceed into the next phase. Otherwise, if their simulation work has much flaws and their answer to the technical questions are not satisfied by the course instructors and enterprise mentors, they have to improve the quality of their work and study more about the theoretical knowledge. If their phase defence presentation is not enough prepared, they have to rework on that.

In this phase, different members in a group have to work in parallel if they would like to improve the efficiency. A member who is good at the application of practical modern simulation tool is more suitable for simulation modelling, a member who is expert in the theoretical analysis is more suitable for simulation result analysis and a exocentric with strong communication skill group member could be the best candidate for presentation. And this division of work based on expertise is the essence of the cooperation and project management. During this process, students' abilities of modern tool usage, problem analysis, project management and cooperation & communication are comprehensively trained.

3.3 Hardware In-the-loop Simulation Phase

The duration of the hardware in-the-loop phase is approximately 4–6 weeks. In this phase, students are required to transfer the SIMULINK model which is a non-real-time simulation model into a real-time simulation model which will be simulated on the HIL simulator based on the rapid control prototyping technology. Two different technical routes of the HIL simulation application will both be experienced by students. Students should combine the HIL simulator as the virtual controller with the physical power electronics modules in order to shorten the development period of the control strategy. After the verification of the control strategy based on the graphical programming software, students should connect a real DSP controller to the HIL simulator which is simulating the power electronic converter. In this way students will not hesitate to develop and download the text-based program into the DSP controller without the hardware failure concerns since the power electronic converter is virtual. Thus both the "virtual controller – physical circuit" and "physical controller – virtual circuit" technical routes are applied in the Hardware in-the-loop simulation phase. As shown in Fig. 6, at this point, the validation and the modification are all up to the group members which is the same as the digital simulation phase.

After the completement of both HIL simulation routes, students should have their second phase defence focusing on the HIL simulation topic. And both course instructors and enterprise mentors are also participate in this defence to judge whether a group can continued onto the next phase.

In this phase, plenty of the infrequently encountered issues would be introduced to the students such as the hardware in-the-loop simulation research method, real-time based rapid control prototyping technology and DSP programming. It highlights one of the most important characteristics of complex engineering problems which is familiarity of issues (CEPA-4). In order to deal with the unfamiliar situations, students have to study relative knowledge during the application of HIL simulator and apply their new knowledge directly to solve the unencountered problems. During this process, students' abilities of modern tool usage, problem analysis, long-life learning and cooperation & communication are comprehensively trained.

3.4 Physical Experiment Phase

The duration of the physical experiment phase is approximately 3–5 weeks. After confirming the feasibility and correctness of the control strategy, DSP programing, hardware circuit assembling through the HIL simulation technology, students finally are able to perform their full physical experiment. In this phase, students have to build a 220 volts AC-DC-AC converter, conduct hardware debugging, and capture multiple waveforms in different working circumstances. Even though a thoroughly theoretical analysis and two difference kind of simulations are performed, the actual experiment result can still be slightly different from the theoretical and the simulation result. That's because commonly the theoretical derivation ignores some of the secondary factors of the circuit. Furthermore, the simulation model is based on the theoretical derivation and the truncation error and round-off error are unremovable nature of the simulation. Hence, the difference analysis of the actual experiment results and the theoretical results is fairly complicated and challenging. On the other hand, even though multiple verification methods have been performed before the physical experiment, it does not change the fact that the voltage of the power electronic converter experiment is above 200 volts and it is far beyond the safety voltage accepted by human being. Hence, the course instructors are required to supervise the students during the whole experiment for safety concerns as shown in Fig. 6. After completing the physical experiment, students are required to prepare a final presentation of the capstone course which including all four phases and both course instructors and enterprise mentors would participate and ask multifaceted questions to evaluate each part of a group's work. Finally, a technical report is required for each student in the capstone course. Since after the capstone course, students will start to work on their graduation projects and write their theses. However, generally a senior year college student hardly has much scientific literature writing experience. This will cause a severe problem when they start to write their graduation theses. Hence, the requirement of this capstone course reports are set as same as the graduation thesis in order to cultivate students' scientific literature writing ability is advance.

After experiencing 16-weeks' including four different and challenging phases, students finally could complete the capstone course study. During this time, 1 theoretical analysis, 3 different simulations, 2 phase defences, 1 physical experiment, 1 final presentation and 1 technical report are required. Following the "tough times make tough designers" educational philosophy, the course design brings students a challenging and struggling time. Furthermore, various kind of theoretical and practical processes in the four phases of the capstone course match with most of the attributes of solving complex engineering problems.

4. The Assessment of Capstone Course

In order to fulfill another important benchmark for evaluating the engineering education qualities which is the continuous improvement, a healthy assessment system is required to feedback the education qualities in time. And capstone courses are often the setting for the development and refinement of complex skills required to be a high performing engineer, because these skills are complex and multifaceted, they are challenging to assess [29]. Observing an object in different aspects would lead to different conclusions, hence, the more aspects we choose, the more objective of the conclusion will be. In our capstone assessment, three aspects of observation are applied which are group members, enterprise mentors and course instructors. The purpose of multi-aspect observation is to transfer a "scalar" score into a "vector" evaluation. As shown in Fig 7, each observation represents a certain aspect of student's ability. The advantage of this assessment system is that each student's strength and weakness can be reflected even though the they got the same total score.

Group Member Assessment: Since the group members are aware of each individual's role in the group including communication with group members, time devoting on the presentations and project

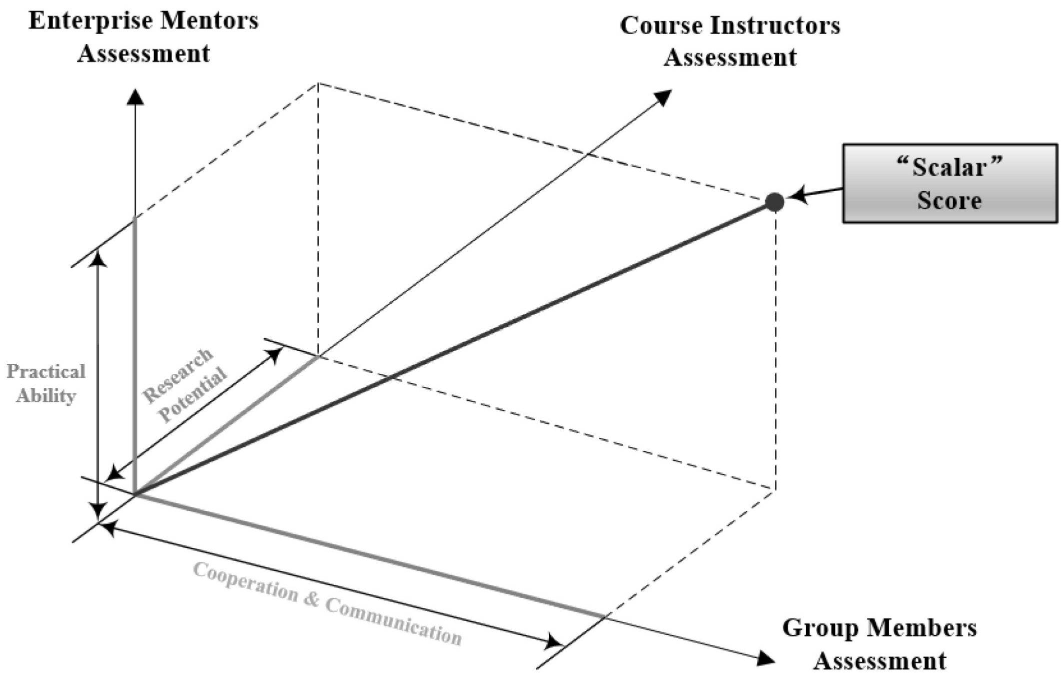

Fig. 7. The relationship between a ''scalar'' score and a ''vector'' evaluation.

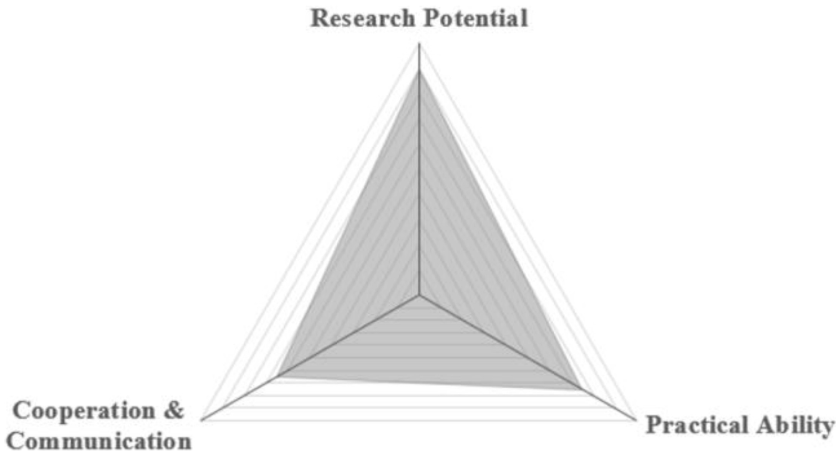

Fig. 8. The 3-dimensional radar chart of student's characteristic.

management etc., it is most appropriate for the group members to assess the cooperation and communication abilities.

Course Instructors Assessment: During the two phase defences and the final prestation, The course instructors assess students' research potential from the aspects of mathematical derivation, circuit analysis and professional theory etc.

Enterprise Mentors Assessment: During the two phase defences and the final prestation, the enterprise mentors assess students' practical ability from the aspects of simulation ability, experimental operation and troubleshooting etc.

With the three different aspect of assessments, a 3-dimensional radar chart can be drawn which indicates three aspects of abilities including research potential, practical ability and cooperation and communication as shown in Fig 8. Each student's characteristic and superiority can be reflected which can be a reference for student's future planning and self-improvement.

Based on the idea of ''vectorized'' assessment, the detail assessment system design is shown in Table 2. The total score is 100. Except the grading of technical report which is 30 in total, all the other 70 scores are graded by the group members, course instructors and enterprise mentors together. In this 70 score in total, the group members' evaluable score is 24 score and both the course instructors' and enterprise mentors' evaluable score are 23. Hence, the distribution of the three score sources is relatively average which is suitable for the ''vectorized'' assessment

Table 2. The grading distribution of the "vectorized" assessment system

<table>
<tr><th colspan="2">Process</th><th>Group Members</th><th>Course Instructors</th><th>Enterprise Mentors</th><th>Total Score</th></tr>
<tr><td colspan="2">Theoretical Analysis Phase</td><td>9</td><td>3</td><td>3</td><td>15</td></tr>
<tr><td colspan="2">Digital Simulation Phase</td><td>3</td><td>6</td><td>6</td><td>15</td></tr>
<tr><td colspan="2">Hardware In-the-loop Simulation Phase</td><td>3</td><td>6</td><td>6</td><td>15</td></tr>
<tr><td colspan="2">Physical Experiment Phase</td><td>9</td><td>3</td><td>3</td><td>15</td></tr>
<tr><td colspan="2">Final Presentation</td><td>/</td><td>5</td><td>5</td><td>10</td></tr>
<tr><td rowspan="3">Technical Report</td><td>Correctness</td><td rowspan="3">/</td><td>20</td><td rowspan="3">/</td><td rowspan="3">30</td></tr>
<tr><td>Format</td><td>5</td></tr>
<tr><td>Writing</td><td>5</td></tr>
</table>

system. And the evaluation basis of each participant in this assessment system will be discussed separately in the following sub-sections.

4.1 Group Members Assessment

The total disposable score of group members is 24 from the four different phases of the capstone course. The disposable score in the theoretical analysis phase is relatively high because this phase is mainly completed by students themselves including independent learning, deduction and discussion and both enterprise mentors and course instructors only evaluate the feasibility of the proposed solutions. Since there are two phase defences in the digital simulation and hardware in-the-loop simulation phase, enterprise mentors and course instructors can evaluate students more objectively from the of theory and practical aspects, the evaluable scores of group members in these two phases are relatively low. In the physical experiment phase, student have to perform a high voltage power electronics experiment in group by themselves which is supervised by the course instructors. They have to troubleshoot all kinds of possible issues including main circuit failure, controller failure and difference between the theoretical and experimental results etc. Since students have a clearer and more objective view of each group member's performance, it is fair that they grant more disposable score in the physical experiment phase. However, it is for sure that problems occur when students have the power to grade themselves. Some of the groups tended to grade every group member the highest score and it is unfair for the other groups. Hence, the solution we came out is that there is a limit score of group member assessment in total in each group, and this will encourage students to grade their group member more objectively since if they divide the total score equally among three group members, no one will get a satisfied score.

4.2 Course Instructors Assessment

The total disposable score of course instructors is 23 from the four different phases and the final presentation evaluation of the capstone course. The disposable score in the theoretical analysis phase is relatively low because course instructors only evaluate the feasibility of the proposed solutions which all came from students themselves. And course instructors play the challengers in the final presentation and two defences of the digital simulation and hardware in-the-loop simulation phase, focusing on ask questions about mathematical derivation, circuit analysis and professional theory aspects which helps the assessment of student's research potential. Hence, course instructors have more disposable scores than the students in these phases.

On the other hand, beside the "vectorized" assessment system, there are 30 more score that course instructors should grade in evaluating the technical report quality of each group. Since this capstone course is organized at the first semester of student's senior year, students will soon start to the work on their graduation projects. And scientific literature writing ability is significant important for the graduation thesis, design report or the scientific papers. Hence, the capstone course provides a suitable opportunity to cultivate students' writing ability and a strict requirement of the course report including the assessment aspects of formatting, writing and correctness will force students to practice and learn the definitely required writing ability.

4.3 Enterprise Mentors Assessment

The total disposable score of course instructors is 23 from the four different phases and the final presentation evaluation of the capstone course. The disposable score in the theoretical analysis phase is relatively low because enterprise mentors only evaluate the feasibility of the proposed solutions which all came from students themselves. As same as the course instructors, enterprise mentors also play the challengers in the final presentation and two defences of the digital simulation and hardware in-the-loop simulation phase. The difference is that they intend to focusing on ask questions about program debugging, simulation operation, experimental measurements and practical troubleshooting which helps the assessment of student's practical ability. Hence, enterprise mentors also have more disposable scores than the students in these phases.

It is worth mentioning that enterprise mentors give student further guidance on the hardware schematics design of power electronics circuit modules which is shown in Fig. 4. This makes up for the course instructors' lack of guidance in hardware design. For instance, a course instructor may teach students the principle and calculator of an operational amplify, but they will not elaborate every register's or capacitor's design. On the contrary, engineers (enterprise mentors) have to figure out every component's function in a circuit (including neglected components in theoretical analysis) in order to optimized the circuit design.

5. Continuous Improvement

In order to improve the quality and efficiency of continuous improvement, a bidirectional assessment mechanism should be established. Previously, the "vectorized" assessment system is introduced in detail, and this assessment is "Teacher assess Student". And a "Student assess Teacher" assessment is also required to realize a bidirectional assessment. Therefore, a survey including concerned questions about the capstone course was sent to the students after the capstone course. And through students feedback analysis and course adjustment, the continuous improvement of the capstone course is realized.

5.1 Questions of the Survey

There are nine questions in the survey as shown in Table 3. Since this paper focuses on discussing the advantage of the course design which is introducing the HIL simulation phase and the "vectorized" assessment system. And these two aspects are new attempts in this capstone course, hence the main concern of the capstone course survey is the performance of the "four dimensional" teaching mode and the "vectorized" assessment system. Question 1, 3, 7, 9 are designed to check the performance of the "four dimensional" teaching mode, and Question 2, 4, 5 are designed to validate the feasibility of the "vectorized" assessment system. Question 6 observes students' feedback on technical report writing requirement and Question 8 observes students' feedback on team work requirement.

5.2 Students Feedback and Analysis

The students feedback of the 2022 spring semester is shown in Table 4. There are totally 81 students in this class and the number of valid survey result is 74 which is over 90% percent of the class. From the comparison and analysis of the relevant questions, the conclusions are drawn as follows:

(1) The difficulty and comprehensiveness of the capstone course is relatively high, especially the HIL simulation phase. Nearly 70% students strongly agree that the course is challenging, and over 80% students strongly agree that the introduction of HIL simulation improves the course quality as shown in Fig. 9. From the survey result comparison of these two questions, it is obviously that the HIL

Table 3. The survey of the capstone course "Comprehensive Design of Power Electronic Technology"

Question	Strongly Agree to Strongly Disagree
1. The assignment of the capstone course is challenging.	① ② ③ ④ ⑤
2. Participation of the enterprise mentors improve the quality of the course.	① ② ③ ④ ⑤
3. The HIL simulation improve the quality of the course.	① ② ③ ④ ⑤
4. The grading policy is healthy and fair.	① ② ③ ④ ⑤
5. Letting students participate in grading is reasonable.	① ② ③ ④ ⑤
6. The requirement of technical report is necessary.	① ② ③ ④ ⑤
7. Your engineering abilities has been improved.	① ② ③ ④ ⑤
8. Your communication & cooperation skills have been improved.	① ② ③ ④ ⑤
9. You understand how to solve the complex engineering problems.	① ② ③ ④ ⑤

Table 4. The survey result of the capstone course

Opinion	Q 1	Q 2	Q 3	Q 4	Q 5	Q 6	Q 7	Q 8	Q 9
Strongly Agree	68.9%	66,2%	81.1%	56.8%	47.3%	62.2%	62.2%	70.3%	71.7%
Agree	21.6%	25.7%	16.2%	29.7%	17.6%	27.0%	18.9%	21.6%	23.0%
Neutral	5.4%	4.1%	1.4%	4.1%	16.2%	9.5%	12.2%	1.4%	4.1%
Disagree	1.4%	2.7%	0.0%	4.1%	6.8%	1.4%	5.4%	4.1%	1.4%
Strongly Disagree	2.7%	1.4%	1.4%	5.4%	12.2%	0.0%	1.4%	2.7%	0.0%

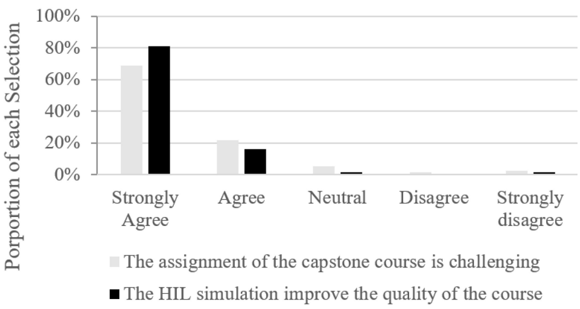

Fig. 9. The survey result of the Question 1 and 3.

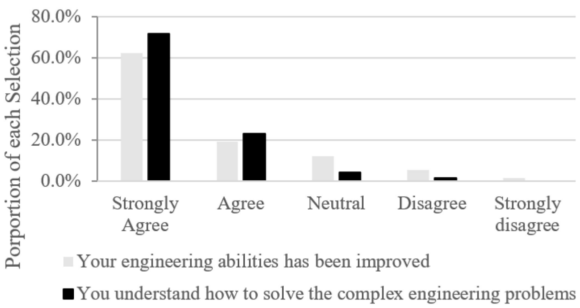

Fig. 10. The survey result of the Question 7 and 9.

simulation phase plays a dominant role in pulling up the total difficulty and quality of the capstone course. And this result shows that the HIL simulation phase may have brought an overly complicated design task for undergraduates.

(2) Student's cooperation & communication and technical report writing abilities have also been cultivated during the capstone course. Over 70% students strongly agree that the capstone course improves their complex engineering problem solving abilities, and only over 60% (10% less than Question 9) students strongly agree that their engineering abilities are improved as shown in Fig. 10. Since the complex engineering problem solving ability also includes the communication & cooperation and technical report writing ability, Question 9's concern is wider than Question 7. Hence, the survey result comparison of these two questions indicates that the capstone course not only improves students' engineering ability through the "four-dimensional" teaching mode, but also significantly cultivates students' comprehensive ability through the strict requirement of technical report writing and multiple presentations.

(3) The students part of grading should be further optimized. Nearly 60% students strongly agree that grading policy is healthy, but only less than 50% students strongly agree that letting students participate in grading is reasonable and nearly 10% students strongly disagree with it as shown in Fig. 11. From the survey result comparison of these two questions, the participation of student in grading

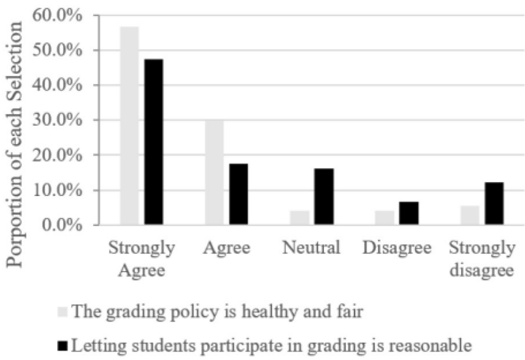

Fig. 11. The survey result of the Question 4 and 5.

pulls down the overall fairness and objectivity of the grading policy, and the corresponding adjustment in student grading should be conducted.

5.3 Continuous Improvement

Based on the analysis of the student survey result, adjustment has been conducted in order to realize continuous improvement of the capstone course in the following three aspects:

1. The difficulty of the HIL simulation phase will be lowered by providing a demo power electronics HIL program which is similar to the design assignment and an additional lecture about the application of the HIL simulation technology will be arranged.
2. The requirement of technical report writing will be further stick to the writing norms of sci-tech literature and all the group members will be required to present in turns during the two phase defences and the final presentation in order to ensure all the students' comprehensive abilities would be cultivated and improved.
3. The rule of student grading will be modified that the grading of each group member of the same group must to be differentiated according to the actual contribution of each group member. The specific approach is to set a maximum total point in each group for distributing the point into each individual.

6. Conclusion

In this paper, aiming to cultivate students' complex engineering problem solving ability, a novel capstone course design is proposed and applied to the Electrical Engineering (EE) capstone course "Comprehensive Design of Power Electronics". This capstone course design includes four main phases including "Theoretical analysis – Numerical Simulation – Hardware in-the-loop simulation – Physical experiment" which formed the "four-dimensional" practical teaching mode. The two distinguished features of the course design are the application of hardware in-the-loop (HIL) simulation and the participation of enterprise mentors in the whole design process. Furthermore, a ''vectorized'' assessment system is developed by introducing three aspects of evaluation including group members, course instructors and enterprise mentors which can transfer a ''scalar'' score into a ''vector'' evaluation. The advantage of the assessment system is that each student's strength and weakness can be reflected even though the they got the same total score. On the other hand, in order to perform continuous improvement of the capstone course, a semester survey about the capstone course is conducted and a bidirectional through teacher and student is established. Thus, the feasibility and reliability of the novel course design and the ''vectorized'' assessment system has been validated and improved.

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