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Teaching Power Electronics with a Design-Oriented and Project-Based Learning Method at the Technical University of Denmark

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Abstract – Power electronics is a fast developing technology within the electrical engineering field. This paper presents the results and experiences gained from Design-Oriented Project Based Learning of switch-mode power supply design within a power electronics course at the Technical University of Denmark (DTU). Project-based learning (PBL) is known to be a motivating and problem-centered teaching method that not only places students at the core of the teaching and learning activities but also gives students the ability to transfer their acquired scientific knowledge into industrial practices. Students are asked to choose a specification from different power converter applications such as a fuel cell power conditioning converter, a light-emitting diode (LED) driver or a battery charger. Based upon their choice, the students select topology, design magnetic components, calculate input/output filters and design closed-loop controllers in order to fulfill the requirements listed in the chosen specification; thereby meeting the corresponding project's goals. In this paper, the course teaching plan and teaching methods are introduced, the assessment method is analysed and feedback from the students is studied.

Index Terms – Project-based learning, group work, power electronics, and DC-DC converters

I. INTRODUCTION

Qualified power electronics engineers need both solid scientific knowledge and rich practical experiences when dealing with emerging and fast developing technologies [1]. To improve teaching effectiveness it is important in power electronics courses to develop students' ability to transfer theoretical knowledge into industrial practice. Power electronic engineers have to be able to cooperate with others as an effective member of a team or group, and therefore require strong communication and problem-presenting-analysis-synthesis skills. Advances in power electronics and emerging demands require changes in both the theoretical (lectures) and practical parts of the education programme of power electronics [2].

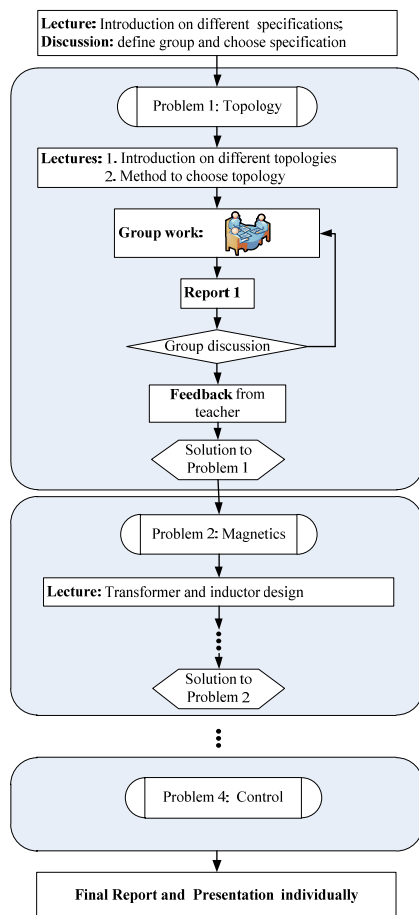
During the last decades, the project-based teaching and learning has been shown to be an attractive method which can improve engineering education significantly [3]-[8]. In general, project-based learning (PBL) is a dynamic approach in which students explore real-world problems and challenges. With this type of active and engaged learning, students are inspired to obtain deeper knowledge of the subjects that they are studying [6]-[8]. Particularly, applying the PBL method to the courses in the electrical engineering (EE) field can increase the challenge for students and thereby their motivation level [9]-[10]. As reported in [7], problem-oriented and project-based learning can offer a

number of advantages. In addition it is very easy to control the learning process.

Some authors have reported using more student-centered approaches in teaching power electronics, such as problem-based and project-based learning, instead of using lecture-based teaching methods. In [11], project-based learning focuses on the magnetic component design of dc-dc converters, in order to help students cope with demanding complexities in magnetics. In [12]-[14], a course using project-oriented design of adjustable speed drives and project-based lab teaching is reported. Both theoretical knowledge and construction practice are involved; so that, students gain hands-on experience as well as improve students' skills in self-directed learning, teamwork and project management. The application of PBL in the subject of designing power supplies has been approved to be extremely positive for students and also for teachers in [15]-[16]. Students are motivated with the PBL scenario compared to the conventional teaching method, additionally teachers can benefit from it in guiding students to achieve significant learning [15]. Moreover, the PBL method has already been widely used in other EE relevant courses, such as analog electronics, communication and power systems, and obtains a promising teaching performance [17]-[20].

In contrast to the reported cases, a unique design-oriented and project-based learning approach is adopted in a power electronics course at the Technical University of Denmark (DTU). Apart from the basic project-based learning method, other activities or tools such as pre-test and peer-assessment are utilized in this course in order to improve teaching effectiveness. Therefore, through this teaching method reform carried out in year 2013, the impact of the adopted teaching approach on student learning, student motivation and student's commutation skills both in oral and report writing, thereby, are investigated and studied comprehensively.

In this paper the description of the course including learning objectives, teaching plan, challenges etc. is introduced, and the analysis of the gained teaching experiences and learning outcomes, and the assessment and students' feedback is given; moreover some suggestions to improve the adopted PBL method are also discussed. This paper is organized as follows. Section II overviews the layout of the course. Sections III presents the process of project-based teaching and learning. Section VI discusses the peer-assessment and its results. Section V and VI describe the course evaluation and the follow-up laboratory course, respectively. Finally, Section VII gives a conclusion.



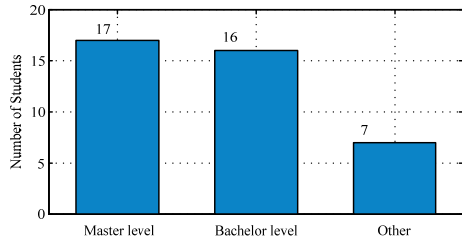


Fig. 2: Number of students in terms of educational level.

From the pre-knowledge perspective and based on the pre-test for the year 2013, the instructors found that many students lacked a deeper understanding of the inductive components' physics; also there was a knowledge gap between feedback control theory and its application on power converters, even though the students had prerequisite courses in basic electrical engineering. Therefore, more teaching materials focusing on those two common issues were added in the corresponding lectures and it shows the effects on teaching by the implemented pre-test.

B. Project work

During the first lecture, the various projects and their corresponding specifications are handed out and thereby chosen by the students depending on their interests and experiences. Based on the common interest, the students can freely form groups consisting of 3-4 group members.

TABLE I: PROJECT CATALOG

1	Power supply for a 2*10W audio power amplifier in a car
2	Power LED string driver
3	Power supply for a Peltier cooler
4	Variable power supply for a SSPA ^a 10W
5	Variable power supply for a SSPA 22W
6	Laboratory power supply 5-30V
7	Laboratory power supply 30-100V
8	Power supply for an IGBT gatedriver
9	Power LED driver
10	Power supply for a Cubesat
11	Power supply for a fuel cell system

^aSSPA=solid state power amplifier=HF power amplifier

The project catalog is given in Table I, so that it is clear that the course PEI mainly focuses on switch-mode power supplies and DC-DC converters. As an example, the specification for the project “#7 Laboratory power supply 30-100V” is given in Appendix I.

In order to provide the knowledge needed to solve the problems in the students' respective projects associated with the corresponding pre-defined specifications, there are 6 lectures given by the instructors. The lectures cover basic power electronics topologies, isolated DC-DC converter topologies, inductor and transformer, input/output filter and close-loop control design of power converters. After every lecture, the students start to do group work to solve the specific problems relevant to their project specifications. The advantage of combining lecture teaching and group work can help students to not only understand the theory and the analysis methods in depth but also promote their capability of cooperation with peers.

For example, in the Topology lecture, the students can learn the operation principles of various non-isolated and isolated converter topologies and also the Component Stress Factor (CSF) method. In the group work, by calculating CSFs of each power converter, the most efficient topology

for the given specifications can be selected. If a Forward converter is chosen for their project, after the lecture on magnetics, a forward transformer with a proper demagnetizing circuit and also an output inductor must be designed during the group work. There are a large number of design parameters to be determined, including air-gap length, conductor area, number of turns, core dimensions for inductors as well as turn ratio, winding arrangement, leakage inductance and isolation for transformers. In the magnetics lecture, due to the limited lecturing time, only the basic magnetic theory, such as applying Ampere's Law in inductor and transformer design, and a general design procedure are described. Therefore, the students have to study literature, text books and other reference documents, and discuss their project with their tutors and instructors and thereby find solutions to their specific project. In this way, the students can develop their problem-solving skills. And this work cannot be completed by a single person, thus they must work in groups and try to cooperate with other group members. In this way, communication and collaboration skills can be enhanced accordingly. Eventually, the final design result is documented in a report and submitted to the instructors for review.

In PEI, each group submits four sub-reports corresponding to the four design problems i.e. Topology report, Magnetic report, Filter report and Control report, as illustrated in Fig.1 and a final report which summarizes all the design work and documents the “paper” switch-mode power converter. Finally, the final report, which is used for the oral examination, is submitted to the external examiner and the instructors.

C. Assessment

Assessment is important for teaching and learning activities, and all the assessment practices must send the right signals to the students about what they should be learning and how they should be learning it [22]. There are two assessment methods adopted in PEI: formative assessment and summative assessment.

The formative assessment is based on the four written sub-reports from which, both the students and instructors can benefit i.e. evaluating the teaching and reflecting on the learning performance during the course. Report writing and feedback from peers and instructors can improve the individual student's learning. On the other hand, by reviewing and correcting the reports the instructors clearly observe the level of students' understanding of the concepts, principles and analysis methods in power electronics, as well as their report writing skills. For example, in the Control report, some students made mistakes of designing a positive feedback loop for the converter. It is probably due to the large amount of teaching materials, the students have difficulties comprehending the essentials of applying electronic components correctly and still lacked practical experiences. The instructors analyze the mistakes in the reports together with the students during the interactive feedback time, and thereby the students can be led back on track to solve the problems and correct mistakes. At the same time, the instructors reflect upon the reasons why students made those mistakes; and accordingly adjust the teaching materials.

For the summative assessment, the students submit a final report based on their 4 sub-reports. Even though the students work in groups during the course, every student has to take the oral examination individually, which means the students need to separately and independently answer the questions raised by the external examiner and the instructors. Eventually, the students were evaluated and graded based on their answers and report.

IV. PEER-ASSESSMENT AND ITS REFLECTIONS

Peer-assessment and peer-learning [23] is a particularly helpful teaching and learning activity for training students to reflect on the quality of their own work. Furthermore, assessment of peers is an important skill for students within technical universities like DTU. In 2013 the peer-assessment method was adopted to review and give feedback on students' reports for the first time. The experiences and results of peer-assessment employed in PEI are discussed as follows.

A. Peer-Assessment procedure

Through peer-assessment, each group is asked to objectively assess the report of another group. But the peer review results do not affect the final grade for each student. The peer-assessment is arranged in 6 steps:

Step 1: Firstly, the groups purposefully matched two by two randomly by the instructors without consideration of the students' projects and background.

Step 2: A lecture is given and at the end of the lecture the report requirements are explained. The students are informed about the peer-assessment of reports and review guidelines are handed out.

Step 3: After the reports are submitted, they are assigned to the corresponding paired groups, and accordingly the report is reviewed by the students in the corresponding paired group.

Step 4: During the interactive feedback time, the students ask questions and give comments to their paired group's report, and the paired group can defend their report. In the process of peer-assessment, an instructor works as a consultant and coordinator, and only if there are some common mistakes or misunderstood concepts, the instructor takes over in order to lead students back on track.

Step 5: At the end of the course, a questionnaire is given and the peer-assessment is evaluated by the students.

Step 6: Finally, the evaluation results are analyzed and possible improvements are formulated for future PEI.

B. Evaluation and reflection

The evaluation questionnaire is comprised of 6 questions as shown in Table II.

TABLE II: PEER-ASSESSMENT EVALUATION QUESTIONNAIRE

Q1	My study motivation is stronger with peer assessment
Q2	I can learn from the other group's report
Q3	Peer-assessment can improve my technical communication skills
Q4	The peer assessment can improve my technical communication skills
Q5	Peer-assessment method is an effective way to evaluate our report and receive feedback from others
Q6	Peer assessment process is arranged well

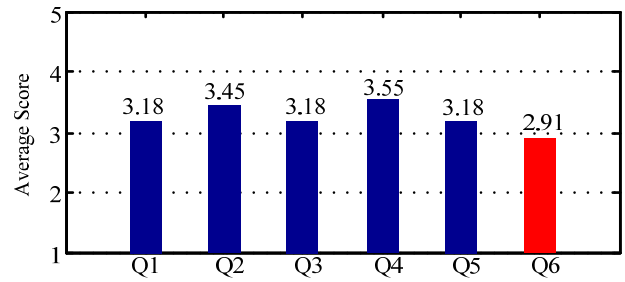


Fig.3: Scaled grade of the results of questionnaire on peer-assessment. (5 means "strongly agree" and 1 means "strongly disagree")

Based upon the answers from 13 students out of 40 (32.5% answering rate), the mean scores can be calculated (5 means "Strongly agree" and 1 means "Strongly disagree") and they are shown on the top of each bar in Fig. 3. Questions Q1~Q5 focus on content and value and the scores are above 3, which is a threshold value of satisfaction. However, question Q6 focuses on form and its mean score is below 3, which shows that organizing peer-assessment was not satisfactory from the students' perspective and should be improved further. Based on these 13 samples, the calculated standard errors (SE) for Q1~Q6 are 0.2822, 0.1977, 0.2822, 0.2978, 0.3595 and 0.3510 respectively. Through observing the peer-assessment process, reading the students' comments and also talking with the students, the instructors found out that the main reason for the low score of Q6 was that one group did not review their paired group's report, therefore the peer-assessment between those two groups was not implemented properly.

Based upon practice as well as the experience, using peer-assessment has advantages as follows:

1. Generally peer-assessment makes the students actively involved in not only report writing but also report reviewing during the formative assessment process.

2. Reports are reviewed from both the instructor's and student's sides. Therefore, report writing skills among various students can be exchanged, and a higher quality final report is expected. The instructors observed that the students were motivated to write an even better report, since their reports were read by peers.

3. Students can learn from each other and can be inspired by other students. For example, some students who are good at the feedback control theory can explain the common mistakes to other students.

4. Students can improve their technical communication skills. Students have the chance to talk with other students in the paired group, so they are able to challenge others and at the same time defend their own work with technical language. It is a very important skill for the students who are studying in a non-English-speaking country like Denmark.

5. Instructors can be inspired by students; students may have new ideas or perspectives on some problems. For example, some students proposed a wireless control method on power converters.

However, from this first trial, it is found that peer-assessment can also be improved if the suggestions below are considered:

1. Consider the different levels of the peer groups;
2. Consider the converter chosen by different groups;
3. Include an intended learning objective regarding the ability to provide peer-assessment, i.e. a direct link between the students' effort in assessing peers and the students' grade;
4. Emphasize that the peer-assessment activity gives the student a critical view upon the quality of his own work, i.e. an indirect link between the students' effort in assessing peers and the students' grade.

V. FINAL EXAMINATION AND COURSE EVALUATION

As previously mentioned, the students are evaluated based upon their final report as well as their performance during an oral examination by the instructors and the external examiner, Christian Wolf, who has been employed since year 2006 at the company Grundfos A/S. The final report assessment criteria are technical accuracy, clarity of waveform and chart, and language with the weighted factors 0.6, 0.3 and 0.1, respectively.

Following the ILOs, the students are graded in the 7-point scale, which is shown in Appendix II. The grade 12 is awarded for an excellent performance, and the grade 2 is awarded for a performance meeting the minimum requirements.

There were 40 students registered for the final examination in 2013, and the statistics on the results is shown in Fig. 4. With the same instructors teaching and the same external examiner in 2011, 2012 and 2013, the grade distributions are given and compared Fig. 5. It can be seen that even though the percentage of students receiving grade 12 is lower in 2013 than the previous two years, the percentage of students receiving grade 7 and above is 92.5% in total, which is much higher than 59.9% in 2012 and 78% in 2011. Moreover, the average grade for the students in year 2013 is significantly greater than that for the control students in year 2011 and 2012 as shown in Fig. 6.

Besides the grade evaluation, there are two more aforementioned assessment metrics of applying the PBL approach: student motivation and student's communication skill. At the end of the course, a questionnaire (given in Appendix III) is used to evaluate the students' satisfaction. The test consists of 22 questions that serve to evaluate several dimensions i.e. Good Teaching Scale (GTS), Clear Goals Scale (CGS), Appropriate Workload Scale (AWS), Generic Skills Scale (GSS), Motivation Scale (MS) and IT Utilization (IT) of the teaching and learning process. The questionnaire was applied in PEI for the first time in 2013. There were 75% students who answered it and the evaluation results are presented in Fig. 6. The satisfaction survey in which GTS and MS are the two best scores can support the instructors' expectation i.e. the students found PBL a motivating way to learn. For example, one student commented in the survey that "PBL and peer-assessment can make me think deeper when I deal with the technical problems"

Regarding the report writing skills, the comments on the final reports from the external examiner are quoted as follows: "The final reports in general are better than the

previous years and there are fewer technical mistakes, improved English and more precise and clear figures and charts.", which shows the improvement of report writing. Moreover, according to the students' feedback, this method can enhance student's capability of spoken technical English language.

However, the score on AWS is only 3.07 and is just above the threshold value of satisfaction, as the lowest bar. Low scores on this scale indicate students' perception of high workload. Actually, it may reveal one feature of power electronics technology; power electronics is a subject which is closely relevant to other subjects such as power system, electronics and control engineering so that it covers the knowledge and skills from those subjects. In this course, to solve the new problem in power electronics converter design, students should synthesize what they have previously learned in other electrical courses with lead to a relatively heavier workload. Therefore, balancing the workload is a big challenge for students and also for instructors in power electronics education.

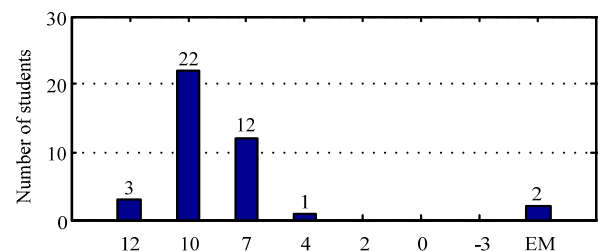


Fig. 4: Student's final grade distribution.

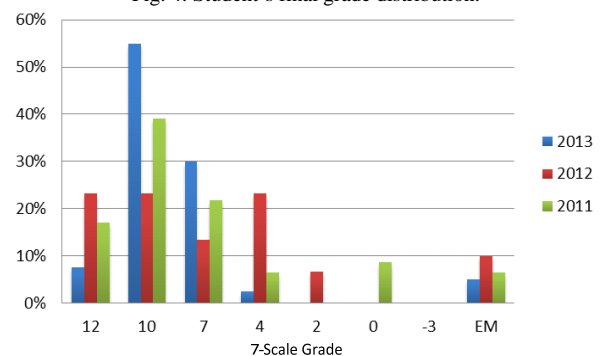


Fig.5: Grade comparison of the previous years.

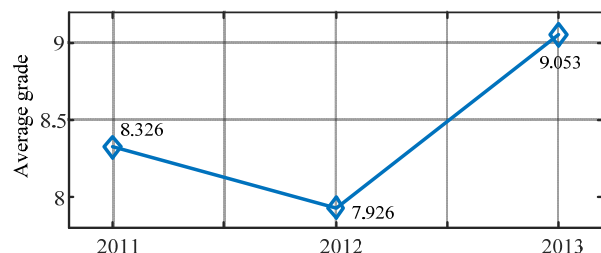


Fig.6: Average grade of year 2011-2013.

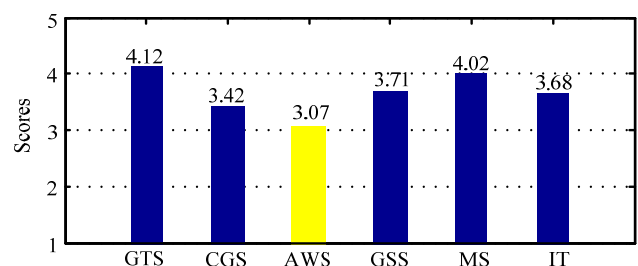


Fig.7: Average scores for the questionnaire on a scale from 1 to 5.

VI. FOLLOW-UP LABORATORY COURSE

After the PEI, the students have the possibility to take the PEII course, which is a 3-week full time laboratory course offered in every January. In PEII the students work in the laboratory and build the converter which they designed on paper in PEI. In January 2014, there were 19 students who took PEI, i.e. 47.5% of the 2013 cohort, decided to take PEII and they built and tested their designed switch-mode power supplies. Moreover, if Master students for whom the course is designed are focused upon, 11 of 17 decided to take PEII which means a high percentage of 64.7%.

A prototype built by the students is shown in Fig. 8. It is a 30-100 V Laboratory power supply, as listed in Table I by using Flyback topology with input voltage of 20~40 VDC. From Fig.8, it can be seen that this converter is comprised of transformer, input/output filter, control and isolated feedback; and the technical knowledge used for converter design is fully covered by the PEI course. Therefore, theoretical analysis and design can well align with practical prototype building. Students demonstrate the abilities to apply their ability on paper to solve realistic problems, and to deal with practical problems in laboratory.

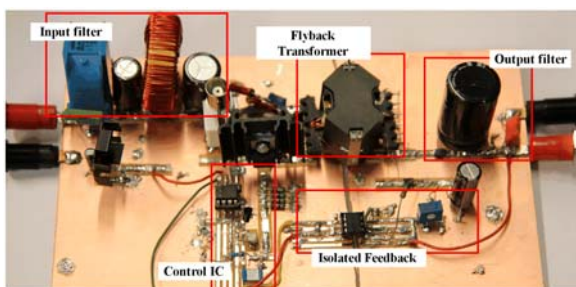


Fig. 8: Photograph of Flyback converter.

VII. CONCLUSION

This paper focuses on a project of teaching students the fundamentals of designing power electronics converters based upon a PBL method. The teaching methods combine traditional teaching, such as lectures and report writing with interactive design-oriented project work. The students work in groups, and carry out their design project. By working on this project design, the students can gain a deep understanding of the fundamentals as well as the important experience of the calculation and design of a real switch-mode power supply. Especially, in the course, peer-assessment as an effective formative assessment approach is employed.

It has been found that changing PEI into a more active learning process can add positive effect upon student learning. The measured student learning is based upon the same ILOs in 2011-2013, and from the grade result comparison, it can be concluded that the change is successful and student learning is improved. The highest scores on GTS and MS in the satisfaction survey as well as the high percentage of enrollment of PEII verify the impact and improvement of student motivation. Moreover, the feedback from the external examiner as well as from the students supports the positive impact on students' communication skill by adopting the peer-assessment

approach. The PBL approach with the new tools such as pre-test and peer-assessment will be applied in the course PEI in the future years and it will be interesting to compare the results again in order to check the validity of the methods adopted.

On the other hand, as learned from the teaching practice, the workload not only for students but also for teachers is still relatively high compared to the traditional teaching methods. When workloads are perceived to be too heavy, students are not able to spend the time needed to engage and understand the material in depth. Therefore, management and control of reasonable workloads under the PBL method could be an interesting topic for future teaching power electronics courses.

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APPENDIX I

TABLE III: Specification of Laboratory power supply 30-100V*:

Input	
Maximum input voltage $U_{in\ max}$	40 V
Minimum input voltage $U_{in\ min}$	20 V
Output	
Maximum output voltage $U_{out\ max}$	100 V
Minimum output voltage $U_{out\ min}$	30 V
Output current range	0~0.3 A
Max ripple mVpp	100
Maximum output power	30 W

*Input and output must be galvanic isolated (at least 1kV-DC//10Mohm).

APPENDIX II

Grading criteria at DTU are given in the Table IV:

TABLE IV: 7-Grade Scale

Grade	Appellation	Description	ECTS
12	For an excellent performance	The grade 12 shall be awarded for an excellent performance displaying a high level of command of all aspects of the relevant material, with no or only a few minor weaknesses.	A
10	For a very good performance	The grade 10 shall be awarded for a very good performance displaying a high level of command of most aspects of the relevant material, with only minor weaknesses.	B
7	For a good performance	The grade 7 shall be awarded for a good performance displaying good command of the relevant material but also some weaknesses.	C
4	For a fair performance	The grade 4 shall be awarded for a fair performance displaying some command of the relevant material but also some major weaknesses.	D
02	For an adequate performance	The grade 02 shall be awarded for a performance meeting only the minimum requirements for acceptance.	E
00	For an inadequate performance	The grade 00 shall be awarded for a performance which does not meet the minimum requirements for acceptance.	Fx
-3	For an unacceptable performance	The grade -3 shall be awarded for a performance which is unacceptable in all respects.	F
EM	No show	The student did not deliver the final report and show up for oral examination	

The Scoring the Student Questionnaire employed is given in Table VI. The questionnaire contains 22 items each with a five-point (1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly Agree) response scale. 21 of these items are a part of five scales and for each scale the item scores are averaged to form scale scores. Only one item is about the use of IT in teaching. This item lay outside the scales. The five scales are: Good Teaching Scale (GTS): Items 3, 5 (reversed), 16, 19 and 21; Clear Goals Scale (CGS): Items 2 (reversed) 6, 8 (reversed), 12 and 20; Appropriate Workload Scale (AWS): 4 (reversed), 15 and 22 (reversed); Generic Skills Scale (GSS): Items 9, 10, 13 and 18; Motivation Scale (MS): Items 1, 7, 11 and 17.

The method to calculate scale scores is: sum the item scores using the scale 5-1; calculate the mean of the sum of the item scores. If there are any missing values then the mean should be calculated using the number of items actually answered.

TABLE V: Questionnaire for Students' Feedback and scores in 2013

Good Teaching Scale (GTS)	
Q3	The teacher normally gave me helpful feedback on my progress (4.43)
Q5	The teacher showed no real interest in what the students had to say in this course (4.13, reversed score)
Q16	The teacher made a real effort to understand any problems and difficulties I had in this course (3.86)
Q19	The teacher has put a lot of time into commenting (orally and/or in writing) on my work (4.24)
Q21	The teacher worked hard to make the subject of this course interesting (3.93)
Clear Goals Scale (CGS)	
Q2	The aims and learning objectives of this course were NOT made clear (3.6, reversed score)
Q6	I have usually had a clear idea of where I was going and what was expected of me in this course (3.60)
Q8	It was often hard to discover, what was expected of me in this course (3.20, reversed score)
Q12	In this course it was always easy to know the standard of work expected from me (3.10)
Q20	In this course it was made clear right from the start what was expected from me (3.62)
Appropriate Workload Scale (AWS)	
Q4	It seems to me that the syllabus in this course tried to cover too many topics (3.33, reversed score)
Q15	I was generally given enough time to understand the things I had to learn in this course (3.23)
Q22	The volume of work necessary to complete this course means that it cannot all be thoroughly comprehended (2.66, reversed score)
Generic Skills Scale (GSS)	
Q9	This course helped me sharpen my analytical skills (3.83)
Q10	This course made me feel more confident about tackling new and unfamiliar problems (3.67)
Q13	The course helped me to develop the ability to plan my own work (3.43)
Q18	This course developed my problem-solving skills (3.89)
Motivation Scale (MS)	
Q1	This course was intellectually stimulating (4.23)
Q7	I have found the course motivating (4.00)
Q11	This course has stimulated my enthusiasm for further learning (4.00)
Q17	This course has stimulated my interest in the field of study (3.83)
IT	
Q14	Where it was used, Information Technology has helped me to learn (3.68)