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Load-Flow Analysis in Power Systems Courses: Comparing Student Learning for Engineering and Engineering Technology Students

Load flow analysis provides an essential vehicle for understanding the state of an electric power system. An ability to perform the load flow and to make appropriate engineering judgments based on its results is an important skill for the power system operator, technologist, and engineer. Both design and analysis facets of the problem are significant in gaining the use of load flow as a tool to design, operate, evaluate, assess and improve the system. In this paper, methods employed by faculty to teach this important topic are assessed at two universities, one of which provide engineering technology programs, and the other, engineering. Each offers its students required or elective sequences in electric power systems. The vehicle for this investigation, one of the fundamental and unifying topics of power systems analysis, is load-flow analysis.

In this paper, the authors describe the importance of load flow analysis as a unifying topic for an introductory course in public electric utility power systems and provide their methodologies for teaching this subject. Their use of various analytical and simulation tools is discussed. These include two primary approaches. First, they approach the subject from a basic programming perspective, using programming language or a mathematics package to write the code necessary to assess the performance of a small power system. Second, they approach the subject from a holistic perspective, using a high-level software package to design a small working power system and then designing and testing improvements to it.

Load flow analysis

The major components of an electrical power system are as follows: transformers, lines, generators, protection and control, and loads. When connected together, these components form a means of safely converting enormous amounts of energy to electrical form, transmitting and distributing it, and delivering it in a useful form to the customer. A load flow is the means whereby engineers and technologists define the orderly operation of the system to deliver energy to the customer. It is indeed a system, requiring a system approach. After models for each major component are defined in appropriate detail, the load flow tools unify these models and perform the calculations necessary to determine the voltage state of the system and the flows of power from bus to bus. Every introductory power systems textbook devotes a significant portion to describing the tools and methods whereby a complete voltage state and power flows are calculated[1].

Typically, learning load flow methods is how introductory steady state power system courses unify and summarize their content for the student. In the course of instruction, the student learns models for each major component: transformer, line, generator, protection, and load. Each model describes component behavior in equations and circuit models expressed in terms of terminal voltage and in consumption or generation of real and reactive power. Developing an admittance matrix unifies the models of the system's components. From the admittance matrix, a set of power flow equations is written, two equations for each bus of the system: one for real power and one for reactive power. The load flow is the means of solving these equations simultaneously. Because a closed-form solution is rarely possible, solution methods are based in either Gauss-Seidel iteration techniques or in Newton-Raphson iteration methods or in some combination thereof.

Historically, to learn load flow methods, students programmed the models of a small system into a computer. Students learned solution methods with this approach, but the time required left little opportunity to modify the system and see what happens when applying various practices for improving system behavior. Some instructors, and an occasionally generous utility, wrote software of widely varying user-friendliness to help students understand these important engineering methods for regulating the system. There was often, and still is, a tradeoff (due to limited available time) between learning the underlying mathematical solution methods and applying the system improvement techniques. It has been observed by the authors that faculty in engineering programs are heavier on programming/mathematical side, while engineering technology faculty concentrated more on “what if” side using available simulation tools.

With the advent of powerful, user-friendly load flow software within the past decade, instructors now have options for teaching load flow concepts in an environment remarkably similar to the jobsite. Graphical user interfaces and fast, reliable computation provide a wonderful opportunity for the student to learn and understand a public utility’s system and to try various methods for improving capacity, performance, and stability. Even financial constraints, though usually stated in an elementary fashion, can be considered when analyzing appropriate proposed improvements. Therefore, these advances in available load-flow software bring engineering and engineering technology students closer in terms of learning both aspects of this important technique.

In this paper, an assessment of learning is reported where these classes of load flow tools are used in laboratories for engineering instruction and for engineering technology instruction. Methodologies are presented for teaching load flow from both perspectives: from a basic programming perspective and from a holistic perspective using a high level software simulation package. The results are assessed and recommendations for improvement are presented.

Programming perspective

A five-bus electric power system presents a significant programming problem without become excessively burdensome. In the work at hand, the power system diagrammed in Figure 1 was presented to engineering students at University of Idaho with its appropriate data[2]. The students were required to program a load flow solution to this problem using Newton-Raphson method.

To prepare them for this exercise, each had already taken a programming language course. They also had the appropriate mathematics necessary to understand both the Gauss-Seidel method, an algebraic iteration approach, and the Newton-Raphson method, a calculus-based iterative solution method. In class, the appropriate models for the transformers, lines, generators, and loads were the subject of the lion’s share of the course, leading to this problem as a capstone requirement.

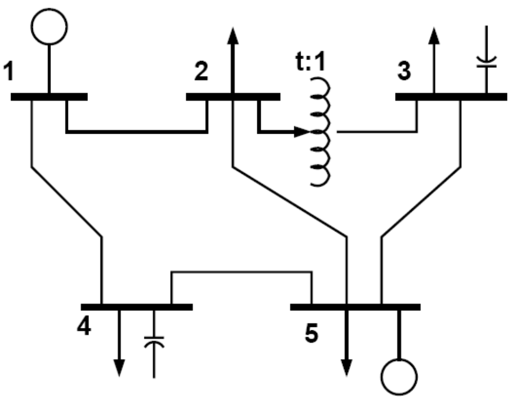


Figure 1a. Topology of Five-Bus Electric Power System for the Programming Exercise

Table 1. Line data.

Line		Per unit series Z		Charging
From bus	To bus	R	X	MVAr
1	2	0.0108	0.0649	6.6
1	4	0.0235	0.0941	4.0
2	5	0.0118	0.0471	7.0
3	5	0.0147	0.0588	8.0
4	5	0.0118	0.0529	6.0

Table 2. Bus data.

	Generation		Load		V	Remarks
Bus	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)	pu	
1					1.01 ∠ 0°	Slack bus
2			60	35		
3			70	42		
4			80	50		
5	190		65	36	1.0	PV (gen) bus

Table 3. Transformer data.

Transformer			
From bus	To bus	Per unit reactance	Tap setting
2	3	0.04	0.975

Assume that the reactance is on the "t" side of the 1:t transformer.

Table 4. Capacitor data.

Bus	Rating in MVAr
3	18
4	15

Figure 1b. Data for the Five-Bus Electric Power System for the Programming Exercise

Of the electrical engineering (EE) students, 85% completed the exercise and found the correct solution. Most of them chose to program in MATLAB® or MathCAD®; the remainder chose to use the C language. These numbers are consistent with observations from year to year, not just for this semester at hand. The choice seemed strongly influenced by the language or program the professor chose for examples. Only 20% of the students wrote what could be described as efficient code. The inefficiencies came primarily in awkwardly programming the loops and in poorly employing subscripted variables. In every successful case, run times were less than 3 seconds. The whole exercise was somewhat shorter in duration for efficient code writers, about 2-4 hours, than for the 65% who wrote inefficient code, 6-25 hours.

Electrical engineering technology (EET) students at Buffalo State were also assigned similar task but this was the first time such an assignment was given to them. Ten students were involved in this project. Their mathematics background varied with three students just being transferred from community college and taking technical calculus concurrently with Power Systems 1 course. Several students did not take programming course yet. Five students were taking MATLAB® and MathCAD® instructions in courses taught concurrently with Power Systems 1. Clearly, their programming experience was not yet as broad as EE students from ISU had. Nevertheless, EET students enthusiastically started on the programming projects. Interestingly, those of them who were taking MatLab instructions in Control Systems course, opted for MATLAB®, and the rest opted for MathCAD® (an example of a three-bus system was presented to them using MathCAD®). None of EET students completed this exercise, although 3 students successfully accomplished it for 3-bus system. The code was written in MATLAB® and similar difficulties with loops and subscripted variables were accounted. Providing more time for the project, the students felt they would have better chances completing it successfully.

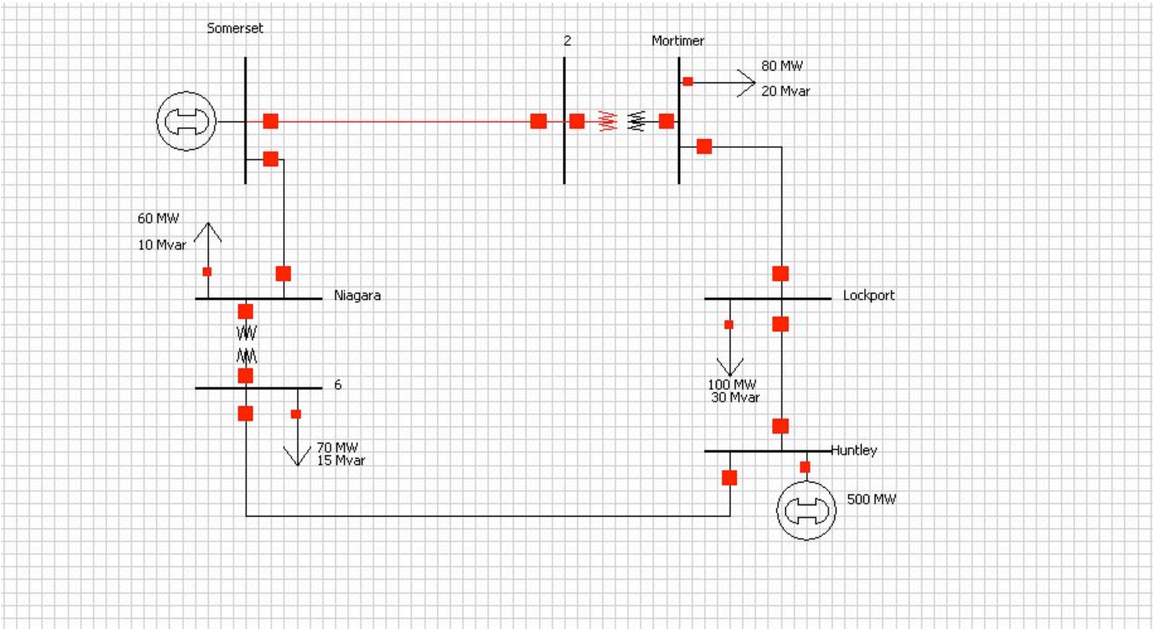


Figure 2a. Simulation Perspective

Bus 1 – swing bus (slack bus); $V_1 = 1.0$ at angle 0 deg.
Bus 5 – voltage-control bus; $V_5 = 1.0$; $P_5 = 500$ MW

Transformers
T1: 345-115 kV; x = 0.1 pu unadjusted; 400 MVA

T2: 345-115 kV; x = 0.1 pu unadjusted; 250 MVA

Lines
115 kV lines: R=32 Ohm/100miles; X=65Ohm/100miles
345 kV lines: R=6Ohm/100miles; X=51.7Ohm/100miles

Line (from – to)	Length, miles
1 - 2	70
3 - 4	55
4 - 5	20
5 - 6	12
1 - 7	20

Base S = 100MVA

Figure 2b. Data for Simulation Exercise

The high level problem, offered to a second group of EE students taking the same course, is shown in Figure 2. The same problem was given to all EET students (it should be noticed that all 10 EET from Buffalo State and were assigned both programming and simulation projects, while 13 EET students from UPJ were assigned simulation project). This is a segment of the public electric utility grid in Western New York. The students were asked to complete the following:
a) Simulate the given power system using a high level program (PowerWorld®[3] was demonstrated for them)
b) Make changes that should improve the system
c) Assess those changes
d) Propose further improvements to the problem at hand.

We assess performance on the high level problem on the following criteria:

1. Completion rate: How many students completed the project at a minimum satisfactory level? Twenty eight engineering students were assigned the project; 25 completed the project at a minimum level gaining a result for the initial simulation. Of those 25, all of them added capacitance and inserted a new line to improve performance, then documented that improvement in terms of better voltage distribution and a capability to handle increased load. All but one student used Power World; the other student, an off-campus student working at a public utility, used EMTP-based software. All 10 Buffalo State EET students completed this assignment successfully. All of them added capacitance and inserted new line or lines. Three students came up with over 10 different scenarios. All 13 UPJ EET students were able to simulate the original power system presented using the PowerWorld Simulator software. However, only 9 of them provided acceptable solutions for the problems associated with the assigned power system

2. How well do they do the work?

a) Use of line capacity: EE students did poorly on this. Most overloaded certain lines, even after adding a new line. They emphasized their success to better distribute the voltages than to avoid line overloads. EET students were pretty successful at this aspect of the exercise. While implementing changes to the system, they monitored both, voltage levels as well as line loading.

b) Achievement of desired values: EE students focused on voltage distribution. Power World® shows voltage levels prominently on its default graphic interface. Consequently, every student who finished the project did a good job in getting voltages within 4% or less of each other when they added a line and some capacitance. More than half (13) did not avoid dangerously loaded lines; they still had serious overloads even after adding a new line. Of the 25 completed projects, 19 did not reduce the generation to match the load, yielding a motoring situation on the slack bus, though 12 of them did report increasing the load to the point of voltage collapse, at about 70% of nominal voltage. One of them, a part-time student who works full-time for the local public electric utility, gave a full report of the loads and voltage levels that appeared prior to system collapse. Innovation consisted of placement of the new lines and capacitors. Nearly all exhibited ingenuity in placing the new line, placing it where it would balance voltages best. Twelve students placed a line in parallel with the most heavily loaded line. The rest balanced the voltage. Four of the students used a tap changer in the line to better regulate the voltage. None used a phase shifter to regulate real power flow. Buffalo State EET students monitored both, voltage and line loading. They simulated changes in loads (real and reactive) and observed how this changes systems behavior. Increases in load were brought up-to the point of system's blackout. At the same time they were experimenting with taking one of the system elements out of service and observing what will happen in this case. On several occasions adding a line was decided based on these considerations. None of them used tap-changing transformers or phase shifters. Motoring action on the slack bus was dealt not by reducing generation but rather increasing the load, although motoring action was noted by all of them with some surprise. All of the UPJ EET students were very surprised to see the generator connected to the slack bus consuming real power (i.e. acting as a motor). The 9 students that provided acceptable solutions to this problem first reduced overall generation at the Huntley bus to alleviate this problem. Then, the students considered the resulting voltages at each bus in the power system and determined if they were within acceptable tolerances. None of the UPJ students modified the real and reactive power requirements at each load bus. The load bus requirements were satisfied by adjusting the generation provided at both the Huntley and Somerset buses. Of the 9 acceptable solutions, 6 of the students merely adjusted the generation at the Huntley and Somerset buses to maintain acceptable voltages at all buses while being careful not to overload any transmission line or transformer. The other 2 students adjusted generation and added capacitor banks in strategic locations to accomplish the same result. Only 1 student adjusted generation and added a new transmission line to provide an acceptable solution to the original problem. None of the UPJ students attempted to add a voltage regulating transformer for reactive power control or a phase angle regulating transformer to manage real power flow. This was surprising since these topics, including a PowerWorld simulation, were covered extensively in class.

c) If incomplete or unsatisfactory, are the reasons fundamental to understanding or incidental? From 3 EE students who failed to complete the project, two did not get the software to work and one did not make any improvements to the given topology. Struggling with the software was the reason for failure. This was surprising because the project was “open neighbor”. Of 10 Buffalo State EET students there were no failures, although it was some frustration during the learning curve after starting new software tool. However, 4 of the original 13 UPJ EET students were unable to provide an acceptable solution for the given problem. At least 2 of theses students made several attempts to change the topology of the original system, but achieved a “blackout” condition. The students became frustrated and gave up on the assignment with the limited time available to complete the problem. Of the remaining 2 students, one made a minor reduction in the generation at the Huntley bus, but the Somerset generator was still “motoring” and the voltage at several buses were out of tolerance. The final student seemed to have an acceptable solution, but did not provide the necessary data to substantiate the results. Also, not all of the capabilities of the program were utilized. The authors did not observe any fundamental reasons. Deficiencies were due to time constrains and due to learning curve difficulties.

3. On an exam that follows (EE students):
Calculation based on understanding of the basic equations: Determine the power flow, given voltages at each bus on the ends of a line and the system’s Y_{bus} matrix: 24 of 25 correct answers. Only one was incorrect, neglecting the line resistance.
Understanding of underlying theory:

- If the mismatch vector is estimated from a small angle approximation, does the power flow converge to the correct solution? 19 of 25 correct answers. Incorrect answers were due to a fundamental misunderstanding of the Newton-Raphson method: the mismatch must converge exactly for a correct solution. This problem was rarely missed in past years, when everyone did only the programming. A correct program requires evaluation of an exact mismatch vector.
- How do we modify the power flow equation set if we change all buses to PV buses? 12 of 25 correct answers. Most of the incorrect responses concentrated on specifying reactive power correction methods to correct the voltage instead of letting a generator at the buses in question do the work. Other incorrect answers were due to confusion about adding load, real or reactive, in other words, not defining the problem consistently. The correct answer is to specify the reactive power at the bus exactly.
- What constitutes a fast decoupled power flow? 23 of 25 correct answers. Incorrect answers due to failure to recognize that the Jacobian becomes constant in a fast decoupled power flow.

The exam seemed to reinforce the notion that those who did the programming exercise seemed to understand the mechanics of the load flow better. They did not understand how to modify the system to achieve a desired change of voltage or power flow state. The opposite is due for those who did only the holistic exercise.

4. On exam that follows (Buffalo State EET students):
Three-bus system was given with the source voltages and real and reactive power load requirements. Students had to design a proper system to accommodate the load. They had to size transformers and lines, calculate their impedance, and determine voltage level at the load bus.

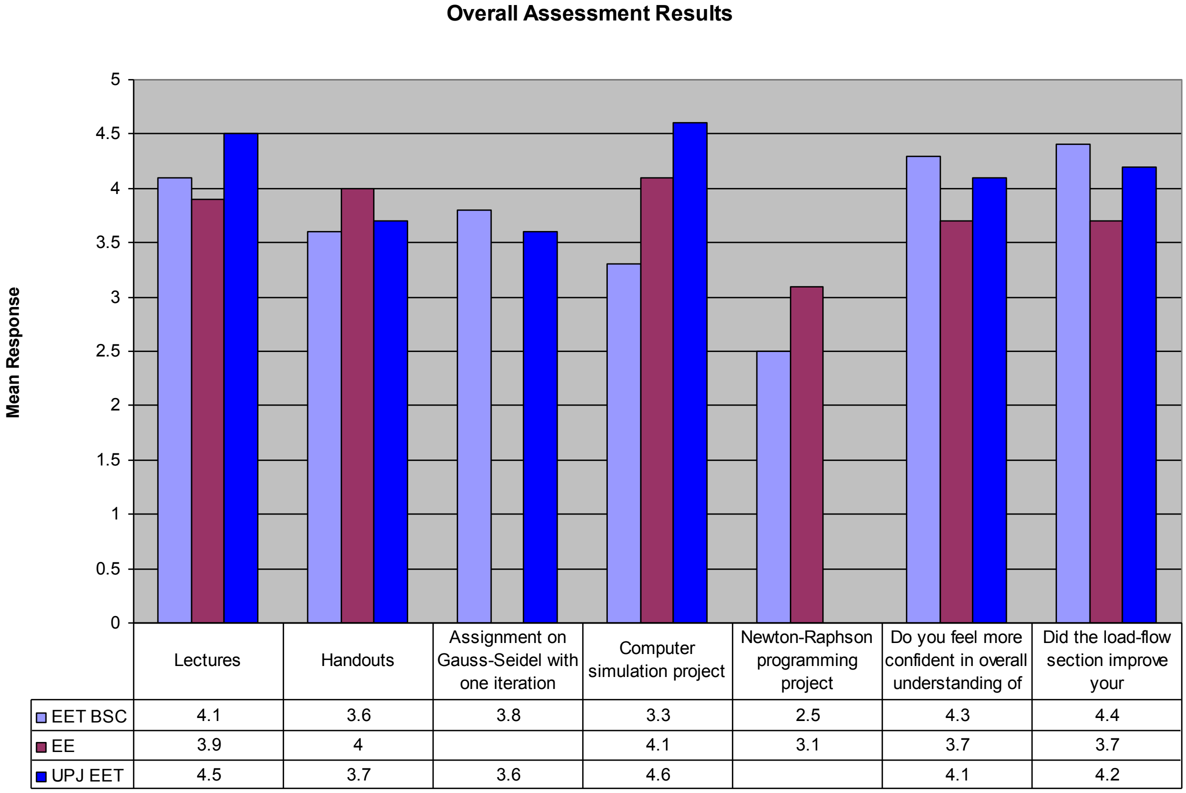
This activity was also combined with economics studies: would it be beneficial to disconnect one line and one transformer with reduced load requirements during weekend days. Design and economic parts of the task were assigned as a home activity, while load-flow calculations were performed in class. In authors' opinion, success (100%) was achieved due to experience gained in simulation project. Students were able to recognize that very low levels of voltage at the load bus were not because of calculation errors but due to system parameters. Correct conclusions were suggested, such as reduction of line impedance, reduction of load (including installing capacitors), utilization of higher source voltage, and even reconfiguration of the system. This final activity provided very valuable experience that design decisions should be verified by analysis of the system.

Student evaluation

Students were asked to complete questionnaires related to assigned activities. The results are presented in Table 1 and shown graphically in Figure 3.

Table 1. Results of Assessment Questionnaire

While studying load-flow analysis, what helped you most to understand the concept?	EET BSC Mean	EET UPJ Mean	EE Mean
Lectures	4.1	4.5	3.9
Handouts	3.6	4.0	4.0
Assignment on Gauss-Seidel with one iteration	3.8	3.6	NA
Computer simulation project	3.3	4.6	4.1
Newton-Raphson programming project	2.5	NA	3.1
Do you feel more confident in overall understanding of load flow after completing above-mentioned assignments?	4.3	4.1	3.7
Did the load-flow section improve your understanding of material in Power Systems 1 course?	4.4	4.2	3.7



	Lectures	Handouts	Assignment on Gauss-Seidel with one iteration	Computer simulation project	Newton-Raphson programming project	Do you feel more confident in overall understanding of	Did the load-flow section improve your
■ EET BSC	4.1	3.6	3.8	3.3	2.5	4.3	4.4
■ EE	3.9	4		4.1	3.1	3.7	3.7
■ UPJ EET	4.5	3.7	3.6	4.6		4.1	4.2

Figure 3. Overall Assessment Results

These assessment results yield the following observations:

1. The students believe that they learned the most from the lectures, followed by the holistic simulation exercise. They felt that they learned the least from programming.
2. There was strong agreement that this section improved understanding of the course material. It was designed as a capstone exercise. It appears to have been successful in unifying the course, at least from the students' perspective.
3. There is general agreement between EET and EE students in the preferred approach to learning when options of lecture, reading, programming, and simulation (with a graphic interface).

Conclusions

This paper compares student learning of load flow techniques as a capstone requirement in an electric power systems course. The requirements were twofold: a programming exercise of a traditional form and a holistic exercise using the latest user-friendly software. For the first requirement, effectiveness of the code, readability, and runtime form a basis for evaluation. Where most of the students finished, the efficiency of their code was lacking. This was more the case for those who used a mathematics package for programming than for those who used a programming language. For the holistic exercise, effective line utilization and voltage distribution form are indicators of a level of understanding. Voltage distribution was well understood and innovations abounded in addressing it. Results in effective line utilization differ between EE and EET students. On a following exam, understanding of underlying principles of equation definition and solution methods were better understood if the student programmed a load flow. Understanding of "what if?" was somewhat stronger among those who did the holistic exercise. As put by one of the Buffalo State EET students: "The more I played with simulation, the more the system acted like a living organism. Adding one part changes the whole system. In doing one change to correct voltage levels you often encounter two or three changes at other busses. It is like a living thing: it seems funny to talk about this in such a way but I hope you understand what I mean by this. Before I started with this simulation project it was just numbers that did not connect in my head. After completion of the project I think it helped me to see the whole idea behind a system as a system. I think that this is a better teaching tool for me. It gives me an idea of how big the real power grid is and what magnitude of problems they face".

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