

VISUALIZATION AIDS FOR POWER SYSTEM COMPUTATIONS

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Abstract

Many electrical engineering programs are caught up in the struggle over what to include as core requirements of the program especially at the senior level. Often, specialty areas compete to have their favorite courses designated as a core requirement. The status, long enjoyed by power engineering courses is however currently being threatened, as more programs no longer see the need to require a power system or energy conversion course. In order to include what the student needs to know about energy systems in the undergraduate curriculum, electric power engineering educators must creatively consolidate course topics that traditionally span two or more courses into one. Traditional pedagogical approach becomes grossly inadequate for addressing the challenges. This paper presents three interactive MATLAB® simulation programs for aiding students in learning three core power system analysis algorithms – power flow, economic dispatch and unit commitment.

Index Terms—Education, Power flow, Economic dispatch, Unit Commitment, Visualization.

Introduction

The challenges of presenting electric power engineering concepts to students in such a way that would bring about clarity, while at the same time keeping students' interest sustained have been highlighted in many research works. While this challenge is not unique to the power engineering field it has however engaged the attention of educators for a while because of concerns that it may be playing a part in their perceived declining interests in the power area over the last decade [1-5]. Power engineering educators have offered an impressive array of

options for addressing the needs. There is consensus on the view that a wider application of digital technology in learning is the key to reversing the undesirable trend. The case has been made for some form of computer-assisted learning environment that is interactive, either as a stand-alone or online web-based collaborative tool [6-11]. These avenues, it is argued, would demonstrate innovative trends in the use of computers, and exploit the capabilities of the Internet for distance education, while providing access to physical laboratory equipment through some form of remote access.

Kezunovic et al [6] related findings of an NSF (National Science Foundation) funded research project aimed at developing new teaching methods for power engineering courses. It noted that computer modeling and simulation were viewed positively and judged to offer more powerful insight into power engineering topics. A variety of tools ranging from custom applications to commercial modeling simulation environment offer features for helping learners make associations between cause (inputs) and effects (outputs), as well as information visualization that are helpful for clarifying concepts. The trend in general-purpose toolboxes and commercial simulation systems is towards user interfaces that facilitate ease of use and quicker development of system models. However, the typical commercial power system simulation program is both comprehensive and complex. It would present a formidable challenge for the average student to learn and demonstrate some measure of competence within the limited time in a three-credit first course in power system. Since undergraduate curriculum needs are not the fundamental criteria in the development of commercial power system packages it should not be expected that they would address conceptual

difficulties students will experience in course of the delivery of a topic. Moreover, the same conceptual difficulties are not necessarily present every time the same course is offered. Difficulty experienced may be due to inadequate preparation of students, or to the style of the course instructor. This would therefore suggest that some form of custom-developed tool is essential, and the better option to adequately address learning needs in the classroom as perceived by the instructor.

This paper presents three custom-developed simulation programs to aid the visual learning process for undergraduates taking an introductory course in power or energy systems. The package developed using the graphical user interface (GUI) toolbox in MATLAB®7.0 [12] brings the graphical interface capabilities into use to enable students to visualize the effects of parameter changes in the configuration of the power system under study. The learning tool enables users to see the flow of information and the intermediate steps or results in commonly used power system algorithms. Commercial power system programs do not routinely offer this flexibility or insight.

The simulation packages were geared towards illustrating three computation problems in power system analysis: power flow (PF), economic dispatch (ED), and unit commitment (UC). These are individually addressed in the sections of this paper.

Power Flow

Power flow studies are of vital importance in the design, planning, and operation of power systems. This underlies the basis of its inclusion in the curriculum. Power flow analysis is fundamentally a three-phase AC circuit problem that should not present a mystery to the typical electrical engineering undergraduate. However, it could quickly become a source of great confusion within the context of a first course in power systems because new elements (transmission lines,

synchronous generator and transformers) introduced into the circuit model, brings along characteristics that elevate complexity of network modeling equations. The per-unit method is used for normalizing data, and to remove the partitioning effect that transformers bring into the problem, while the bus admittance technique is used for organizing network data. A numerical solution algorithm, such as Newton-Raphson is commonly used for iteratively obtaining bus voltages, currents and power flows. Derivation of the power flow equations, generalization for the n-bus system and reorganization of equations into compact vector/matrix form should precede discussion of the Newton-Raphson algorithm (Appendix). This array of new concepts could unduly impose on the limited time to cover other important concepts. It therefore behooves the course instructor to seek options for quick clarification of the concepts and processes.

Power systems simulation programs have been around for many years. Some of the prominent ones include Positive Sequence Load Flow (PSLF) [13], PowerGraph [14] and PowerWorld [15]. Although targeted towards educational uses PowerGraph does not offer the user insights on computations performed in the background. PowerWorld on the other hand is highly interactive and offer some animation and attractive visual metaphors to facilitate learning. It is integrated into some power system analysis textbooks; however it is primarily commercial software which was not designed to target specific academic learning objectives.

In this section two visual aids developed for clarifying the power flow solution process is presented. The first attempts to explain the process or method for solving the power flow problem without getting into all the fine details of the solution. A flowchart representation of the problem, via Newton-Raphson method, is displayed. The user could review the solution of the problem step by step, as shown in Fig. 1, thereby obtaining comprehensive understanding of the problem and method used in its solution.

The user is given access to a number of parameters of the power system through the visual interface of Fig. 1. For instance, the designated system slack bus may be changed through a pull-down menu or a transmission line eliminated on the “Modify System” group. Transmission line impedance and susceptance may be modified as desired through the menu on the “Modify Line Data” section, where Line 1 2, for instance denotes the connection between bus 1 and bus 2.

Students are exposed to the mathematical equations being used to represent the system, the type of parameters being calculated at each step, how and which of the parameters change during each numerical iteration. The active flowchart updates parameters in real time. In

other words, the package exposes the student to the process taking place behind the typical graphical representation of the system in commercial software packages.

The second approach uses a graphical representation of the system in the form of the power grid. To decrease the abstraction of the system representation, the conventional one-line diagram is not used in this approach. This is because the average student in power engineering courses, have difficulty comprehending and relating the one-line diagram to the physical existence of the system. Therefore, the system is represented as a power grid in which lines are drawn in a shape similar to real transmission lines as shown in Fig. 2.

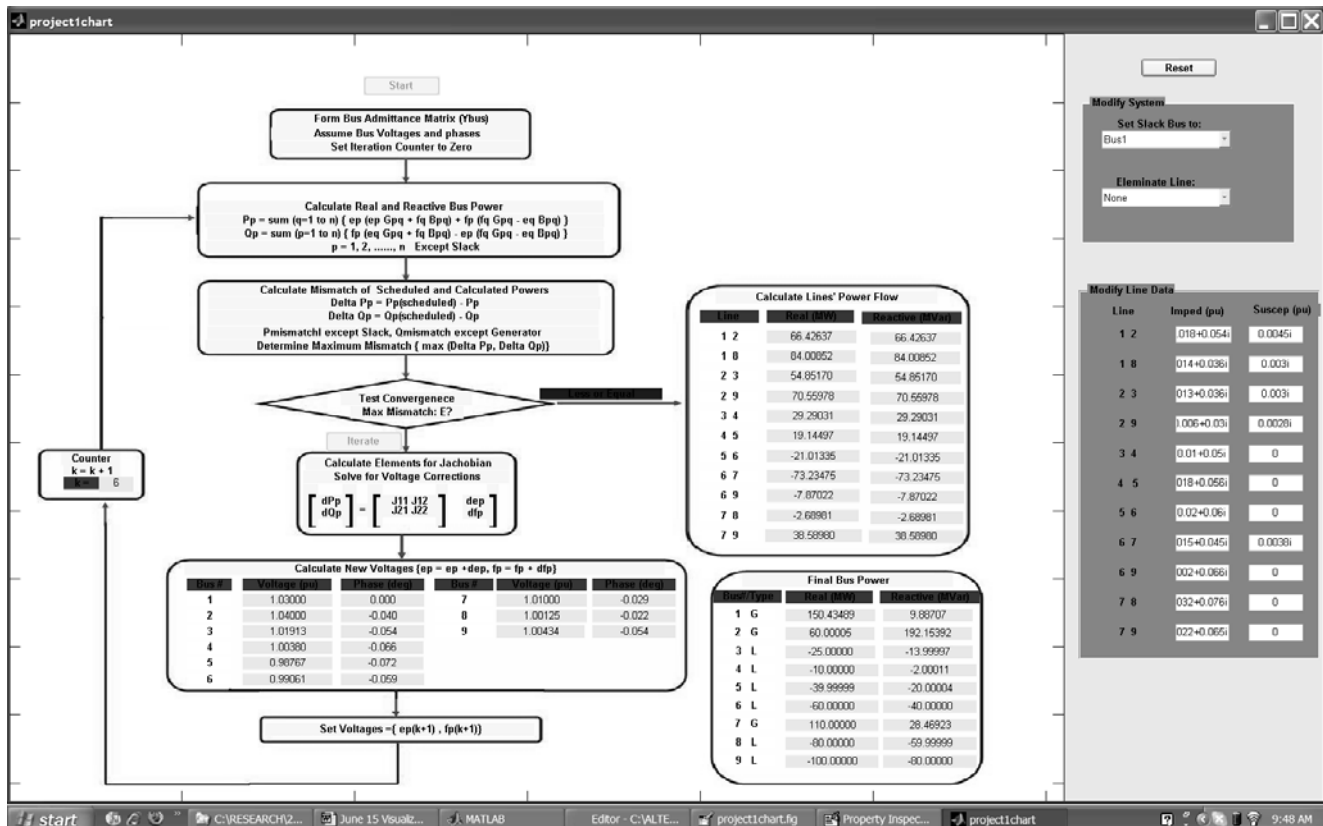


Fig. 1. Power Flow Visualization (Flow chart).

Further, pictures of industrial or residential areas depict loads, while generating units are displayed as real pictures of power plants. This representation enables students to relate the problem to the physical power system and its parameters. The package enables users to obtain a final, complete solution of the problem where the quantities are displayed over the grid and directions of the line-flows are shown with arrows. The user may elect to solve the problem iteratively where the solutions of each of the iterations are displayed over the grid.

One of the main concepts illustrated by the package is the classification of buses. In general, there are three types of buses: load bus, generator, and swing or slack bus. At a load bus, the real and reactive powers are held fixed during power flow studies. For a generator bus, the controlled variables are the bus voltage

magnitude and the real power output, while at the slack bus voltage magnitude and angle are pre-specified. This bus classification is illustrated in the iterative method; the user would notice the variables that change at each iteration and the ones that remain fixed. Further, the package menu enables the user to change line impedance values and bus type designation, or even disconnect transmission lines from network. This offers the student a learning environment for in-depth understanding of the role and effect of these parameters on the power flow study and operation of the system.

The power flow visualization tool is designed for a 9-bus power system but may be modified or adapted for a smaller or larger system. This requires access to a MATLAB® programming

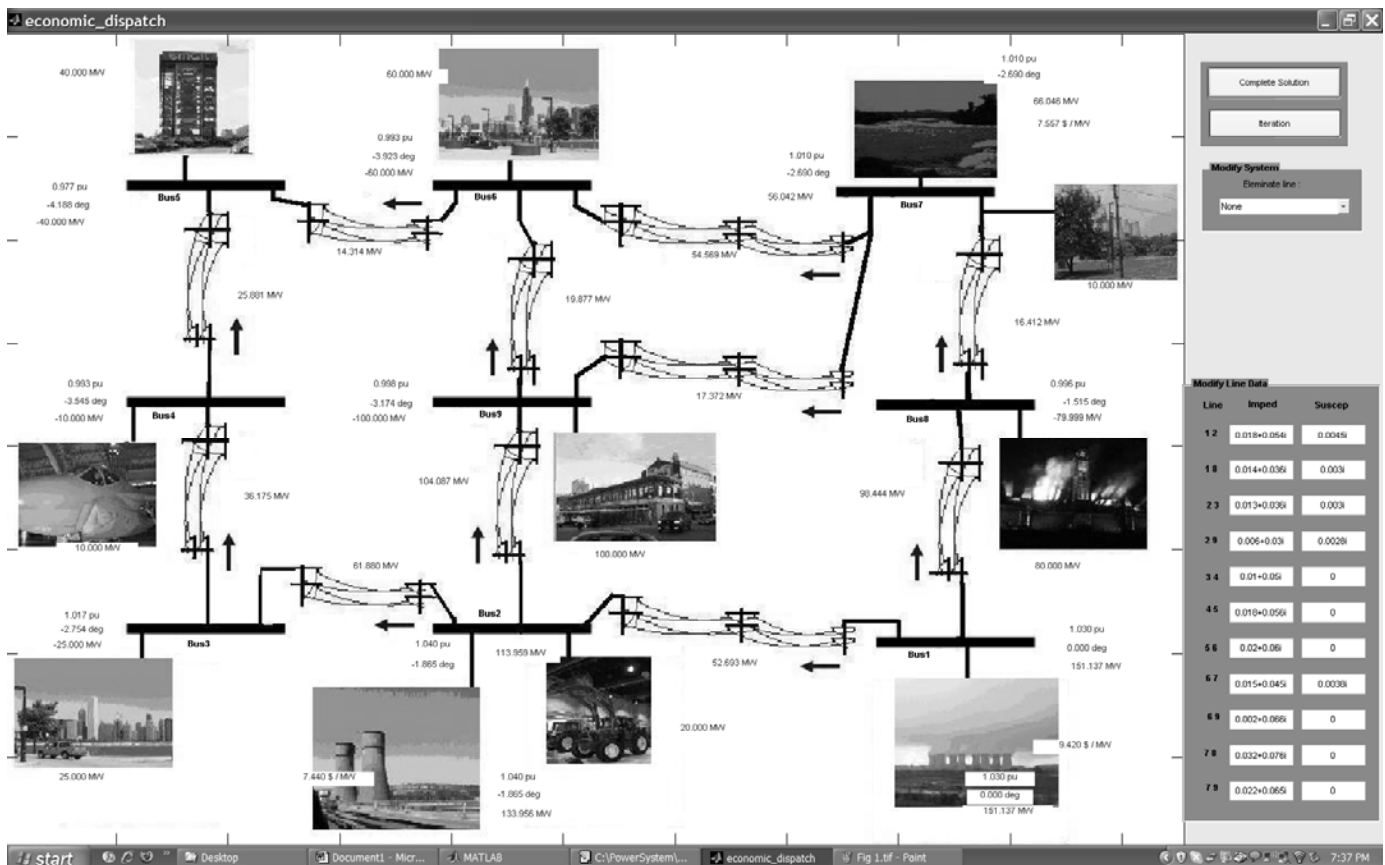


Fig. 2. Power Flow Visualization (Power grid).

environment. The source code for the visualization tool is free and accessible from the download website - <http://peteridowu.googlepages.com/>.

Economic Dispatch

The modern power system such as exists in North America is an interconnection of several generator groups, thousands of miles of transmission lines and blocks of demand loads. The infrastructure provides the critical medium for assuring some measure of electric system reliability, and an avenue for economic allocation of generator outputs to ensure system-wide loss minimization. In its simplest form the economic dispatch (ED) problem attempts to minimize power production costs and line losses, within constraints of physical limits or requirement of power system elements.

The information obtained from the ED study includes the power output of each generator unit, voltage magnitude, phase angle, power flows and losses on lines. Further, the ED study would inform the operator of the actual and incremental cost of delivering power to satisfy a certain demand level in the system. This topic should have a place within the first course in power system, given the fact that it highlights an area of application where power production costs and energy loss reduction on a large scale have long been the tradition.

The problem is traditionally formulated as a constrained optimization problem, and solved using the Lagrange multiplier method [16] (Appendix). The resulting nonlinear problem is solved iteratively, with required power flow analysis within the iteration of the ED solution algorithm. The challenge is centered on how to present this concept concisely within the first course in power system. In order to demonstrate some grasp of the concept the student would need an understanding of the Lagrange multiplier method, an iterative solution technique for non-linear equations, and power flow analysis.

The approach to the ED problem visualization is similar to that proposed in the power flow case. First, a process description is used in a form of flowchart (Fig. 3) to illustrate and provide an understanding of the mathematical representation and the iterative Lagrange multiplier method. Working with this form of the ED problem representation, the user is guided through the steps involved in solving the ED problem. The role of each equation and the effect of the parameters on the optimal solution are easily observed. This provides an in depth understanding of the process taking place in the background of the typical graphical representation in commercial packages. In addition to the flowchart view, Fig. 3 shows critical system parameters that may be changed. A line could be eliminated from the system by making a selection from the "Modify System" pull-down list, changes are made to generator cost functions from the "Modify Cost Function Coefficients" group and transmission line data from the "Modify Line Parameters" group.

A graphical representation of the ED problem, similar to that described for the power flow problem shown in Fig. 2 is provided to the user. The user may view a complete solution of the problem or iterate through each step. Further, user could change system parameters, such as line impedances and generator cost function parameters, or view the effect of transmission line removal on the performance of the power system. In addition, the user can review how the incremental cost of each generator changes iteratively.

Unit Commitment

The unit commitment (UC) problem is a formulation of the process for determining start-up and shutdown schedules for generating units in order to satisfy load forecast requirements at the minimum cost. It is generally unfamiliar to typical electrical engineering undergraduates as the subject falls outside the scope of

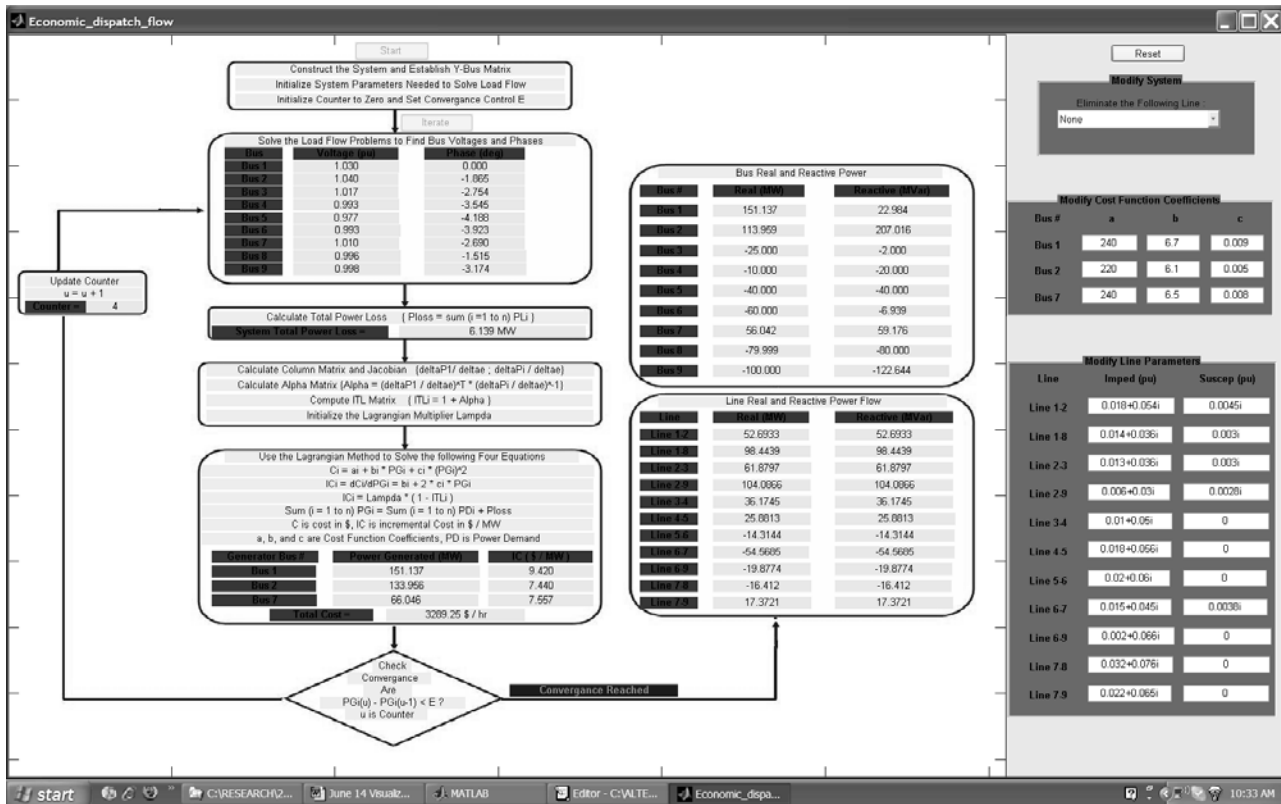


Fig. 3. Economic Dispatch Visualization (Flow chart).

introductory level power engineering course. The subject however touches on physical or practical limitations of energy conversion devices, the knowledge of which could yield further enlightenment and broaden the perspective of the student. The UC problem solution factors in generator minimum up time and downtime before de-committing or re-committing respectively, must-run units, spinning reserve and crew constraints, among others. The dynamic programming algorithm [16, 17] performs a “forward pass” to determine minimum “production cost” of possible combinations of generators over each interval of the forecasted demand. This is the sum of economic dispatch (ED) costs of generators in each feasible set. The forward pass is followed by “backward” sweeps to recursively determine the least total cumulative cost to arrive at the final interval by summing production and transition costs between intervals.

For the unit commitment visualization tool only a subset of the parameter are considered, such as the cost associated with starting and shutting down of units, and the maximum and minimum power output capability of the generating units. Further, only a lossless case of the power system is considered. A sample system comprised of four generating units, with some “must-run” constraints is used to demonstrate the UC problem. In the graphical representation of the problem, a grid is constructed for six stages of the load cycles, in which each node depicts the availability of a particular generator group and the cost associated with it, as shown in Fig. 4. The visual tool interface provides access to generator cost function coefficients, minimum and maximum generator power settings, system loading during each stage of load cycles, and interactive buttons to initiate dynamic programming.

The interactive solution method consists of two main sweeps. The first is a backward sweep in which the solution determines the availability of the generator group and its operation cost in each of the six stages of the day. A forward sweep follows the previous one to determine sequence of generator groups that would result in the minimum and efficient solution. The user is able to follow the step-by-step process of dynamic programming and how decisions are

made at each stage. Further, the package enables its user to change certain system parameters, such as the total load levels during the six cycles of the day, the maximum and minimum real power output of generating units, and the cost function parameters of the generator units. Therefore, the user would gain understanding of the role and effect of these parameters on system operation, cost and performance.

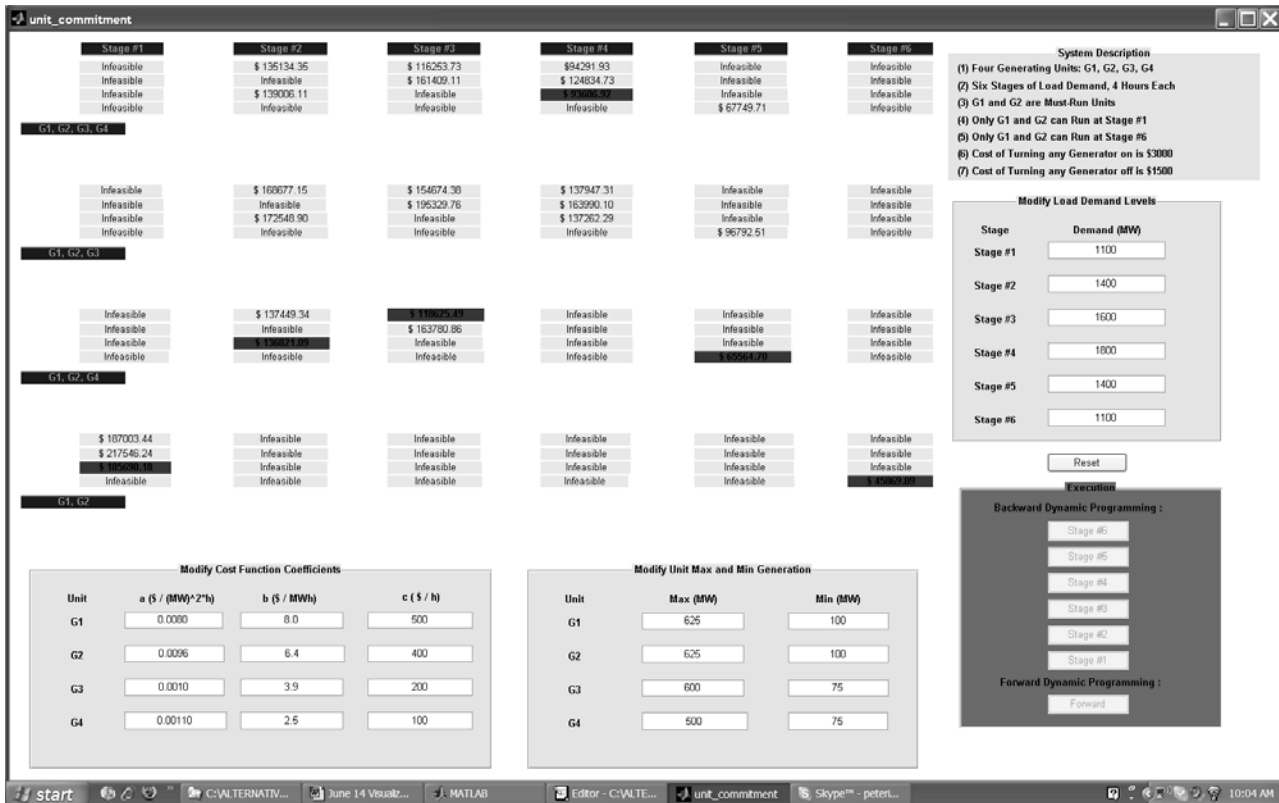


Fig. 4. Unit Commitment Visualization.

Conclusions and Future Improvement

This paper presents three MATLAB® based simulation programs to aid the visual learning process for undergraduates taking an introductory course in power systems analysis and computations. The tool enables students to visualize the effects of changes in the configuration of the power system under study, and to observe the flow of information and the intermediate steps. The simulation tool focuses on three important power system analysis problems: power flow, economic

dispatch, and unit commitment. Although some commercial power system programs offer free educational versions with limited features, they do not routinely offer the insight on the computation process. The flexibility does not exist for users to modify the program in order to address learning needs in the undergraduate classroom. Since the proposed simulation tools is implemented with a readily available development environment: MATLAB®, it improves accessibility to students. Also, it offers an

avenue for course instructors to improve the learning environment by targeting simulation models to address learning needs. The wider use of user-developed simulation tools will ensure that important concepts and processes that require clarifications will receive due attention in course of the ever-shortening length of time to accomplish it. The three simulation programs are available for download from: <<http://peteridowu.googlepages.com/>>

Appendix

Newton-Raphson power flow problem [16]:

$$I = Y_{Bus} V \quad (1)$$

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \quad (2)$$

V and I are bus voltages and currents respectively. δ and $|V|$ are voltage angle and magnitude respectively, and P, Q are bus powers. J_1 through J_4 are system Jacobian sub-matrices.

Economic dispatch problem for N generator system [16]:

Minimize $C_t = \sum_{i=1}^N C_i(P_{gi})$; subject to:

$$\sum_{i=1}^n P_{gi} = P_L + P_D$$

Where $C_i = \alpha_i P_{gi}^2 + \beta_i P_{gi} + \gamma_i$.

C_i is the fuel cost function and P_{gi} is the power output of unit i . α_i , β_i , and γ_i are quadratic cost function parameters. C_t is the total cost, while P_L and P_D are the total loss and demand respectively.

Unit commitment problem for generators over k intervals [16-18]:

$$F_{i^*}(k) = \min_{\{x_j(k+1)\}} \{P_{i^*}(k) + T_{i^*j}(k) + F_j(k+1)\}$$

$P_{i^*}(k)$ is the minimum production cost of combination $X_{i^*}(k)$. $T_{ij}(k)$ is the cost of transition from combination $x_i(k)$ to combination $x_j(k+1)$ between intervals k and $(k-1)$. x_{i^*} is the best combination for a given stage (or interval).

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