A Power Systems Capstone Design Project and Associated Simulation Software Designed to Meet the Changing Needs of the Electrical Power Industry and Engineering Accreditation Requirements

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Abstract

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Although rarely a concentration of university research, power systems pedagogy should be of significant concern to power systems educators. This is particularly true in undergraduate education where industry is currently demanding that graduating seniors be better prepared to contribute to the practical needs of industry. In response to recent changes in industry, academia, and government, ABET is requiring that undergraduate engineering students complete a significant design project which reaches significantly beyond the purely technical. The power systems industry is also changing rapidly. The liberalization of electrical power markets is requiring that engineering students have a better understanding of economics and public policy in addition to technical knowledge. Although these broader issues should be addressed throughout a power systems curriculum, the capstone course is a good place to integrate technical and non-technical knowledge into practical design projects. In this work a capstone design project was developed which integrates market economics, socio-political issues, and transient stability analysis. This project meets nearly all of the ABET requirements for a capstone design project. Additionally, a software package was developed which uses visualization

and a simple user interface to aid students with the design/analysis process. A new method of using color to code transient stability machine curves was developed and implemented. This thesis covers the historical background behind recent changes in engineering education, describes the transient stability project and the simulation software, and presents the results of initial user tests.

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Preface

Before reading this document it may be helpful for the reader to know the assumptions I have made that inform the following chapters. My first assumption is this: that there is a strong interrelationship between differing subject areas. What I mean is that whether one is studying sociology, mathematics, biochemistry, theology, or electrical engineering, the material one is studying is related to the material others are studying in other disciplines. Because things relate, Blaise Pascal, the 15th century physicist, mathematician, and theologian, was able to use his extensive understanding of scientific inquiry to create some of the most rigorous theological treatises of his day and then use his relentless search for theological truth to inform his search for an understanding of the mathematical properties of a cycloid curve. I think, for the same reason, Albert Einstein's views of the political and social issues surrounding the Second World War were both informed by and respected because of his landmark contributions to scientific thought. Additionally, Einstein's broad world-view affected the way he approached scientific inquiry. In 1931, he published an essay called, "The World As I See It," in which he writes, "… I am a deeply religious man...I am satisfied with the mystery of life's eternity and with a knowledge, a sense, of the marvelous structure of existence -- as well as the humble attempt to understand even a tiny portion of the Reason that manifests itself in nature." In this same essay he writes of his passion for social justice, social responsibility and democracy. These values informed the way that he approached science, just as his understanding of science informed his religious, social, and political beliefs.

The second assumption I bring to this work is this: that we as people have a divinely-given role in making the world a better place for living. I think that engineers are not excluded from this responsibility. Engineers have a responsibility to consider how to do "applied science" that will leave the world a better place for it having been done. If engineers are to competently consider how to best contribute to a better world, I think they must make a sincere attempt to understand the societal context in which their new technology will be utilized. I believe that those who are best prepared to contribute technologically to the world in which we live are those who have a broad background in the humanities and deep moral convictions. Likewise, those who are best prepared to contribute to society through the humanities and social sciences will increasingly need to understand technology as the technological becomes an increasingly important part of everyday life. I think that the moral responsibilities and challenges of engineers should be more clearly emphasized in engineering education. Both the IEEE [Inst, 01] and the National Society of Professional Engineers [Nati, 01] have clear and helpful codes of ethics that can be guides for integrating instruction on moral judgment into engineering education.

In light of these assumptions, this work draws on a wide variety of sources from a variety of academic disciplines. In this work, I hope to take a look at how we can take an engineering science, such as electrical power systems, and create methods and means for teaching this material in a way that considers the context and needs of students, and encourages students to consider the context for which they are engineering. In this way it is hoped that students will be inspired to pursue the difficult-to-measure and rather nebulous ABET Engineering Criterion [Engi, 97], that students would be "lifelong learners."

Acknowledgements

Firstly, I wish to acknowledge the Supreme Author, who engineered time and life to enjoy it with us. I join with the Psalmist in singing,

> The Lord is God, and he has made his light shine upon us…
> You are my God, and I will give you thanks;
>   you are my God, and I will exalt you.
> Give thanks to the Lord, for he is good;
>   his love endures for ever. (Psalm 118:27-29, NIV)

Secondly, I want to acknowledge my parents without whose help and constant encouragement I would never have finished this degree or much of anything else. Particular thanks is due them for spending long nights arduously pouring over my high school English and History papers until my mediocre writing became something bearable to read. Thanks is also due my brother, Philip, and other good friends who have helped to preserve my sanity by consistently encouraging me to quit studying to go climbing, hiking, or out for a good meal.

I wish to also acknowledge Professor Rich Christie for his contribution to this work and to my education in general. His regular insight and careful criticism has been invaluable to this research, and has taught me to think more critically and ask good questions about both my own work and that of others. Thanks are also due to Professors Cindy Atman, Mark Damborg, and Chen-Ching Liu for their help and suggestions.

1 Introduction

Normally, the general public gives little or no thought to the source of the electricity that comes out of the wall socket. They know that they get a bill for it once a month and this is all that they normally need to know. Recently, at least on the West Coast of the United States, this has changed dramatically. A search on *Yahoo.com* of the news during the week of 24 February through March 2, 2001 revealed 117 stories in major newspapers and online news sources about the electrical energy crisis on the West Coast. Electrical energy is an important part of urban life world-wide. In the United States, as in most developed nations, electricity is extremely dependable and therefore is often thought of as an inherent right as opposed to a product which can be bought and sold. The recent energy crisis in the Pacific coastal states is shocking because the electricity that has historically been so reliable and relatively inexpensive is suddenly unpredictable and high-priced. Although there are technical problems which have contributed to this crisis, a strict understanding of only the technical side of 60Hz Alternating Current electricity will not solve the problem. This problem, as with many other energy it in the world energy market, are necessarily economic problems because electrical energy costs money. Energy problems are also economic because power systems are increasingly being turned over to the guidance of Adam Smith's invisible hand—to the laws of supply and demand. The laws of economics must be carefully obeyed if good solutions are to be implemented. Energy problems are also political. Government officials scramble to create emergency fixes and to attempt to prevent cascading damages to society and thus their political careers. Ultimately, power systems problems are social problems because the power system has a very direct and widespread effect on people.

In my mind one of the most important roles of engineering education is to prepare students to solve the most difficult technical problems which society will face in the next generation. Today, many of the most influential people and agencies in engineering education are claiming that the technical problems that engineers will face in the next generation require a broad range of non-technical skills in addition to a deep understanding of science and technology. This is certainly true in the case of the West Coast energy crisis. At the very least, power systems university programs should be graduating engineers who have expertise in the science and technology of power systems and enough understanding of non-technical subject areas to work in teams with specialists in the other disciplines to develop innovative and effective solutions.

In light of the above needs, this thesis is the result of an effort to develop solutions for power systems education that lead to the training of engineers to meet tomorrow's power systems challenges. There are two primary technical contributions of this work. The first is the development of a power systems design project that causes students to combine technical analysis skills with non-technical ones. The project requires students to study the transient stability of a system, evaluate the effect of the stability limitations economically and socially, and then recommend changes that are technically, economically, and politically justifiable. The design problem was implemented in a course entitled "Computer-Aided Design of Power Systems" at the University of Washington in the spring of 2000.

The second technical contribution of this work is the development of an integrated package of power systems analysis tools which use visualization to help students quickly perform analysis tasks. Although this software is largely based on previous power systems visualization work, there are a few new contributions in the program. The program is the only known education-focused computational tool which uses visualization as the primary means of presenting calculated results. A new method of using color to correlate transient stability machine curves with their respective buses was implemented in the software. Preliminary user responses to the program have been quite positive, although initial empirical tests did not show much advantage over less visual power analysis software.

This thesis is structured into five main chapters (chapters two through six), the conclusions (chapter seven), and this introduction. Chapter two gives a brief history of electrical engineering education from its inception as a separate discipline in the late 1800s until the present. Of special interest in this chapter are the historical shifts between application-focused education and science-focused education. Chapter three looks at the rationale behind capstone design and the challenges of implementing capstone design courses in the context of power systems education. Chapter four describes the transient stability design problem in detail, along with the tools and models developed for this problem. Chapter five describes the PowerViz software which was developed for use with the power systems design problem. Chapter six discuses an initial set of user tests conducted using the PowerViz software. Finally, chapter seven draws some conclusions and makes some recommendations for future work.

> "The world in which electrical engineers live and work is evolving swiftly in several dimensions at once. Progress in everything from integrated circuits to communications and power keeps raising the bar on the sheer quantity of knowledge that engineers need today. The emergence of multinational corporations with flatter hierarchies has turned such traditionally non-engineering skills as communication and management into prerequisites of functioning effectively in industry. For these reasons, universities and industry are looking hard at electrical engineering curricula and modifying them, in some cases drastically."
>
> IEEE Spectrum Sept. 1995[Gepp, 95]

2 A History of Electrical Engineering Education

Since the first university level Electrical Engineering (EE) programs were created in 1891, engineering program designers have struggled to maintain a balance between science and application in the EE curriculum. The first EE programs leaned heavily on the physics departments of their respective universities and contained generous portions of math and science. As EE programs became independent departments within engineering schools near the turn of the century, the program requirements changed to include more application-focused coursework. When the United States joined World War II, the demand for new military technologies increased dramatically, yet most electrical engineers were not sufficiently prepared in math and science to make meaningful contributions to the state of the art. Numerous engineering educators saw this as a deficiency in EE curricula and proposed that expectations and standards change to include more math and science. As schools adopted the new system during the late 1940s and 1950s, many universities gained large government research grants to support engineering science research. Many engineering professors became focused primarily on research, and undergraduate education became a lesser priority. Most courses gave little opportunity for students to interact with the material outside of lecture and textbook problems. By the late 1970s, employers began to complain that the research coming from academia was of little practical value and struggled to find electrical engineering graduates who had the practical skills required to be successful engineers. As the cold war ended in the early 1990s engineering programs and societies concerned with engineering education began to investigate ways to adapt engineering programs to be relevant to the contemporary needs of society. These investigations are currently leading to major shifts in the content and pedagogy of electrical and other engineering programs throughout the United States.

This chapter will trace the history of electrical engineering education from the late 19th century until the present day. Of special interest are the swings between application-oriented content and science-oriented content and corresponding changes in pedagogy. Since the changes are not only affecting EE education, much of what is written here will also apply to other engineering disciplines.

2.1 From the Inception of Electrical Engineering to Before World War II

On September 4, 1882 the Edison Electric Light Company opened the famous Pearl Street Station, within which six "dynamo" generators furnished sufficient DC power for 7200 electric lights [Webe, 94]. By 1887 Thomas Edison's company had 121 stations in operation spread throughout the United States [Webe, 94]. In 1885, the American Telephone and Telegraph (AT&T) Company was formed to connect and operate intercity telephone and telegraph networks. In 1897 the Marconi Wireless Telegraph Company was incorporated to implement Guglielmo Marconi's wireless communication technologies. These new industries required specialized electrical engineers to meet the growing demand for electricity and communications. In order to meet this new demand, universities began to establish specialized electrical engineering programs. The first of these were established in 1882 by Werner von Siemens, a founder of the German Siemens Company, within the technical universities of Stuttgart, Darmstadt, and Berlin-Charlottenburg [Webe, 94]. Also in 1882 the Massachusetts Institute of Technology (MIT) offered "an alternative course in physics…for the benefit of students wishing to enter upon any of the branches of electrical engineering" [Term, 98]. In 1884 this officially became the "Electrical Engineering Program," but remained within the physics department until 1902 when a separate department was created. The early MIT curriculum was largely comprised of physics and humanities courses (see Figure 2.2). This curriculum differed substantially from engineering curricula at contemporary non-electrical engineering schools. "According to the president of Rensselaer Polytechnic Institute, Palmer C. Ricketts, most engineering schools in the 1890's imparted 'a smattering of so called practical knowledge' and produced 'surveyors, and…mechanics, rather than engineers'" [Seel, 99]. Some sought to alter the curricula to be more like European engineering schools with a stronger emphasis on math and science, but these were the exceptions rather than the rule. Most engineering students spent large portions of their time in shops and laboratories learning the details of working with materials and technologies. Due to the nature of the subject, electrical engineering schools continued to be highly connected to the physics departments of US universities until the turn of the century, and thus contained a higher concentration of natural and engineering sciences than other engineering disciplines. As electrical engineering departments became members of engineering colleges and distanced themselves from physics departments, emphasis on practical skills increased while math and science instruction decreased.

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COURSE IN ELECTRICAL ENGINEERING.

First Semester—	Hours	*Second Semester—*	Hours
Freshman Year.			
Plane Trigonometry, 1a	4	Analytic Geometry, 2a	4
Higher Algebra		Higher Algebra, 2a	
Chemistry, 1a	4	Chemistry, 2a	4
Mechanical Drawing, 1	4	Descriptive Geometry, 2a	4
English Composition, 1	4	Plane Surveying, 3a	4
Shop, 1a	2	Shop, 1b	2
Physical Culture, 1	2	Physical Culture, 2a	2
	16+4		16+4
Sophomore Year.			
Analytic Geometry, 5a	3	Calculus, 6a	4
Differential Calculus, 5b	3	Industrial Chemistry, 2a	4
Physics, 1a	6	Physics, 2a	5
Machine Design, 5a	3	Machine Design, 5b	2
Elem. of Steam Engineering, 6	2	Engines and Boilers, 7a	2
Shop, 2a	2	Shop, 3b	2
Physical Culture, 3	2	Physical Culture, 4	2
	17+4		17+4
Junior Year.			
Mechanics, 5a	4	Mechanics, 5b	5
Political Science, 1a	4	Dynamo Machinery, 1b	2
Dynamo Machinery, 1a	2	Dynamo Lab., 1c	4
Electrical Measurements, 4a	4	Dynamo Design, 1e	1
Primary and Secondary Batteries, 5a	2	Electrical Measurements and Photometry, 4b	2
		Steam Engineering, 13a	2
Total	16	Total	16
Senior Year.			
Hydraulics, 6a, 6b	4	Hydaulics, 6b	1
Electric Railways, 2	2	Telegraph and Telephone, 9	2
Power Transmission, 8a	2	Power Transmission, 8b	2
Alternating Currents	3	Alternating Currents, 6b	3
Alternating Current, Lab.	2	Alternating Current Testing, 6d	2
Commercial Testing, 7	3	Thesis	4
Total	16	Total	14

Figure 2.1 – University of Washington EE curriculum for the 1904 – 1905 school year [Univ, 04]

In order to teach the practical skills which employers were looking for in engineering school graduates, curricula in early EE programs were heavily composed of laboratory and practical design courses. For example in 1904-1905, the University of Washington EE curriculum included 2 full years of "shop" and all of the EE courses concentrated on one specific EE technology such as the "Dynamo" generator, power transmission, or telephone and telegraph [Univ, 04]. There were no general electrical engineering science courses such as the present analog circuit and electronics analysis courses.

This application-focused method began showing some limitations during World War I when new electrical technologies were developed including "wireless" or radio communication technology and the vacuum tube. Most of the innovation in these new fields came from scientists trained in the physical sciences, as few electrical engineers had the knowledge of advanced math and science needed for the development of such technologies. Since EE students were not extensively trained in the basic sciences behind the new technologies it was difficult for them to be effective participants in the development and implementations of new technologies. At this time, only a few graduate programs in engineering existed, and those that did exist were not large enough to make major contributions to the state of the art. Despite the fact that undergraduate engineers did not have a deep scientific background, graduate education was not considered necessary to work in the growing power, communications, or electronics fields. In fact, according to Terman, "some employers felt that a college man with a master's degree was less useful to them than a man with a bachelor's degree, since in their opinion the former had wasted a year by hanging around college and thereby avoiding facing up to the real world" [Term, 98].

2.2 From World War II until the End of the Cold War

In 1942 the United States joined the war in Europe. This had major implications for electrical engineering education and technology, in addition to the impact it had on society in general. US engineering school enrollment dropped sharply during the war as most eligible engineering applicants joined the armed forces. Simultaneously, the war created a demand for numerous new technologies. In the electrical field these technologies included radar, microwaves, control systems, electrical navigation systems, atomic energy, and new types of electrical instrumentation. This increased demand brought generous US military research grants to engineering schools (primarily from the Atomic Energy Commission), which far surpassed the few industry sponsored research programs that existed before the war [Seel, 99]. Since pre-war engineers were primarily trained in engineering practice, with very little experience in scientific theory, physicists were once again the primary developers of new war technologies. Post-war engineering academicians recognized that if engineers were to be more than merely surveyors and mechanics and participate in the world of innovation, engineering curricula would need to include more science.

Before World War II, several engineering educators had tried to reform engineering curricula to include more math and science but had little success. Before the war, there was paltry demand for engineers who had better preparation in the natural sciences than in practical application skills. During the post-war period systemic change was feasible, as there was an abundance of research and education funding from the US government and thousands of men returning from the service interested in working with new wartime technologies. Three of the most influential academicians promoting this change were F. E. Terman at Stanford, S.C.

Hollister at Cornell, and E. A. Walker at the University of Illinois. All three strongly believed that engineers should have thorough training in math and science, and that this should be taught in the context of their applications whenever feasible. While Hollister was the Director of the School of Civil Engineering at Cornell he created a class in differential equations for engineers in which students were taught mathematical theory in the context of its applications [Seel, 99]. He believed that math and science were indispensable tools for the engineer, and that engineers should be taught to use them effectively. Hollister, Terman and Walker each revised their respective programs in the mid to late 1940s to reflect these new priorities, and published several papers promoting a new role for math and science in engineering education [Seel, 99]. In 1951-1952 Hollister, who was at that time the president of the American Society of Engineering Education (ASEE), launched a major ASEE study on American engineering education. This study resulted in the *Report on Evaluation of Engineering Education* [Grin, 55]. This report, more commonly known as the Grinter Report (after the chair of the ASEE Committee on Evaluation of Engineering Education), became the standard by which new engineering programs were to be evaluated. The introduction to this report reads:

> Engineering Education must contribute to the development of men who can face new and difficult engineering situations with imagination and competence. Meeting such situations invariably involves both professional and social responsibilities. The Committee considers that scientifically oriented engineering curricula are essential to achieve these ends and recommends the following means of implementation:
>
> 1. A strengthening of work in the basic sciences, including mathematics, chemistry, and physics.
> 2. The identification and inclusion of six engineering sciences, taught with full use of the basic sciences, as a common core of engineering curricula, although not necessarily composed of common courses.
> 3. An integrated study of engineering analysis, design, and engineering systems for professional background, planned and carried out to stimulate creative and imaginative thinking, and making full use of the basic and engineering sciences.
> 4. The inclusion of elective subjects to develop the special talents of individual students, to serve the varied needs of society, and to provide flexibility of opportunity for gifted students.
> 5. A continuing, concentrated effort to strengthen and integrate work in the humanistic and social sciences into engineering programs.
> 6. An insistence upon the development of a high level of performance in the oral, written, and graphical communication of ideas.
> 7. The encouragement of experiments in all areas of engineering education.
> 8. The strengthening of graduate programs necessary to supply the needs of the profession…
> 9. Positive steps to insure the maintenance of faculties with the intellectual capacity as well as the professional and scholarly attainments necessary to implement the preceding recommendations…[Grin, 55]

Both the ASEE and the Engineers' Council for Professional Development (the predecessor to the Accreditation Board for Engineering and Technology, ABET) were instrumental in implementing the changes that Hollister, Terman and Walker had begun [Seel, 99]. The above criteria promoted in the *Grinter Report* became the foundation on which ABET built its early accreditation requirements. In 1965 Walker was president of the ASEE and began another study that found that the American engineering schools had effectively implemented the new curricular concentration in the 20 years leading up to 1965. The tremendous success of these reforms is well expressed by Terman in 1976 when he asserts that, "never again will electrical engineering have to turn to men trained in other scientific and technical disciplines when there is important work to be done in electrical engineering" [Term, 98].

Despite the widespread acceptance of the recommended changes there were some drawbacks to the new EE education system. Universities became more and more focused on research supported by military and space program grants, and became less connected to industry. The shift from supporting industrial practice to theoretical research was so dramatic that a historian at Purdue noted that when "the engineering editor tried to get pictures to illustrate reports on research in progress, he was sometimes told there was nothing to photograph unless he was willing to photograph an equation" [Seel, 99]. Many felt that EE research was no longer applied science, but rather a basic science of its own. Complaints from industry began to arise that the work being published in journals was too removed from engineering practice to be of any practical use. Even those most influential in the shift of focus from application to science were unsatisfied with the growing separation between industry and academia. Walker wrote, "'The danger for engineers…is that they can become too enamored of research for its own sake. A good engineer…must strike a balance between knowing and doing'" [Seel, 99]. Another implication of the new focus on EE research was that faculty research success became a far greater factor in the university reward system than quality undergraduate instruction. Less effort was expended to engage undergraduate students in class work. Since there were fewer laboratories attached to engineering courses students often had little opportunity to interact with the material other than through lecture and problem solving.

Another setback for science and engineering education came in the mid 1970's. The early years of the Cold War and the "Space Race" provoked a major thrust toward improving US science and technology education systems. The perception that Soviet space projects were repeatedly outperforming corresponding US projects lead many to advocate reform in the US science and technology education system. This brought a flurry of National Science Foundation (NSF) sponsored projects aimed at incorporating various forms of active scientific inquiry into education. Unfortunately these projects did not lead to system-wide improvements because according to the NSF, "simple complacence set in after the US became the first nation to land on the moon, which was taken as a clear (!) signal that the problem had been solved, and presumably once and for all" [Melv, 95].

2.3 Recent Changes in Electrical Engineering Education

Electrical engineering programs retained their focus on engineering science until the late 1980's and early 1990's when Soviet communism collapsed and the Cold War ended. With the end of the cold war, government funding for military and space research dropped significantly. Simultaneously, increasing globalization was (and still is) changing the types of products that were produced in the US and those that are imported. Also, new technologies based on high-density semiconductor systems, including the personal computer, were flooding the market. While semiconductor technologies certainly had military and space applications, the major forces driving the industry were civilian, not governmental. Changes in the global and US economies caused a demand for electrical engineers with new skill sets. Research partnerships between companies involved in the new economy and academia increased, allowing some schools to replace former military and space research grants with industrial ones. This increased industry participation in engineering education allowed changes that had been desired for some time to actually take effect. This is currently leading to a shift in engineering education, increasingly refocusing it on producing students who are well prepared to do engineering design under real world constraints and with the non-technical skills needed to effectively participate in the new global economy.

During the 1980s the NSF, the National Science Board (NSB), and the ASEE released several studies again recommending changes to engineering education. One of the foremost results of these studies was a call for engineering education institutions to include formal instruction in the design process in engineering curriculum. One of these reports is the ASEE's "A National Action Agenda for Engineering Education" published in 1987 [Davi, 87]. In this report the ASEE asserts that creating design tasks that have an element of reality, yet are feasible within the time-constraint of an undergraduate engineering course is a difficult task. The report notes that, "Many engineering educators believe that the use of open-ended illustrative problems in engineering courses in place of idealized mathematically tractable ones will better prepare students for engineering practice. However, the time required to prepare and grade open-ended problems may be prohibitive. The challenge is to develop a series of real-world problems that take advantage of the computational capabilities of today's engineering undergraduate while recognizing the constraints of faculty time" [Davi, 97]. The report promotes that the NSF fund the development of transferable design curriculum and projects for all engineering disciplines. Soon ABET made such design curriculum a requirement for accreditation. The ABET accreditation criteria for the 1989-1990 academic year reads:

> (a) Engineering Design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation. The engineering design component of a curriculum must include at least some of the following features: development of student creativity, use of open-ended problems, development and use of design methodology, formulation of design problem statements and specifications, consideration of alternative solutions, feasibility considerations, and detailed system descriptions. Further, it is essential to include a variety of realistic constraints such as economic factors, safety, reliability, aesthetics, ethics, and social impact.
>
> (b) Courses that contain engineering design normally are taught at the upper-division level of the engineering program. Some portion of this requirement must be satisfied by at least one course which is primarily design, preferably at the senior level, and draws upon previous coursework in the relevant discipline. [Accr, 89]

This quickly became the standard as engineering schools required students to take at least one semester or quarter of "capstone design" or "senior design," in which students were asked to complete some significant design project and communicate the results.

Although change had begun in engineering schools, many felt that academia was still producing engineers inadequately trained for the post Cold War US economy. In response to this the ASEE launched another major study in 1993. This study was a joint effort between the Engineering Deans Council and the Corporate Roundtable of the ASEE. This joint effort between industry and academia was intended to make the needs of industry a major factor in the process of determining where engineering education most needed to improve. According to the chair of the Corporate Roundtable, Norman Augustine, the study began because, "engineering education needed a new set of guiding principles to replace those that had been developed following World War II. Rather than a world based largely on superpower competition and national security, engineers now faced a world of intense international economic competition and widespread public uncertainty about the uses of technology" [Engi, 94]. The result was the so-called "Green Report" which recommends that engineering education become:

> + **Relevant** to the lives and careers of students, preparing them for a broad range of careers, as well as for lifelong learning involving both formal programs and hands-on experience;
>
> + **Attractive** so that the excitement and intellectual content of engineering will attract highly talented students with a wider variety of backgrounds and career interests—primarily women, under-represented minorities and the disabled—and will empower them to succeed; and
>
> + **Connected** to the needs and issues of the broader community through integrated activities with other parts of the educational system, industry and government. [Engi, 94]

The NSF has also made extensive recommendations for changing engineering educational systems. Much of NSF's work has had a broader scope, recommending changes to all of "Science, Math, Engineering and Technology" (SME&T) education. One major NSF report emphasized that, due to the increasing importance of technology in daily life, undergraduate SME&T education should be available to all students and not only those who plan to enter SME&T careers. Specifically, this report urges that, "All students have access to supportive, excellent undergraduate education in science, mathematics, engineering, and technology, and all students learn these subjects by direct experience with the methods and processes of inquiry" [Melv, 95]. This report emphasizes that SME&T education should be available to students in both two and four year schools, that the education should be supportive so that students who have traditionally turned away from SME&T education will be encouraged to pursue it, that the programs be excellent so that students who pursue SME&T careers can compete at a "world class level," and that all undergraduate education give students opportunities for scientific inquiry.

In another report, the NSF recommends the following four areas of change for engineering education:

> 1. *Engineering Education Must Encourage Multiple Thrusts for Diversity*. Even though engineering and engineering education are more diverse now than in the past, challenges to our society demand even more, in both kind and degree, including:
> * Educational and professional diversity among faculty;
> * Ethnic, racial, and gender diversity among faculty and students
> * Diversity in academic backgrounds and experiences among students; and

> * Diversity in planned educational experiences that respond to the demands of a diverse workplace including integrative laboratory experiences which promote inquiry, relevance, and hands-on experience in a variety of contexts.
>
> 2. *Engineering Education needs a new system of faculty rewards and incentives.* Faculty perceive the present system to focus on disciplinary research and publication; this focus must be expanded to include teaching, research, advising, and service in a way that includes all faculty as valued colleagues.
>
> 3. *Assessment and evaluation processes must encourage desired expectations for both faculty and students*: New approaches to assessment must judge faculty contributions across the expanded spectrum; methods for evaluating student efforts must promote student learning; and careful assessment of teaching and learning is needed to identify successful educational innovation and encourage adaptation/adoption by others.
>
> 4. *The changes needed for engineering education require comprehensive change across the campus, not just in the engineering college.* As reflected in the previous items, colleges and universities must take new approaches toward students, faculty, and curricula. These changes can not credibly be limited to engineering colleges, but will necessarily entail a comprehensive reform of undergraduate education. [Meye, 95]

This report focuses on programmatic changes that are needed to implement broad changes in engineering education. The report spends considerable time expressing a need for engineering courses and projects that require students to think more broadly than has been done in the past. They recommend that, "the contents of the new curricula reflect…a broad range of concerns: environmental, political and social issues, international context, historical context, and legal and ethical ramifications of decisions" [Meye, 95]. The report advocates more widespread use of interactive projects in engineering curricula, which appropriately utilize multi-media technology and advanced pedagogical methods.

The National Research Council (NRC) has also been actively involved in the recent engineering education restructuring. In 1995 they published the report: *Engineering Education: Designing an Adaptive Approach*. This report recommends a broad range of practical measures that schools of engineering can take to implement recommended changes. In this report the NRC asserts that no one method of change can work for all schools, but that each school should evaluate its program in order to determine methods of adapting to a changing world. The themes are similar to those expressed by the NSF and ASEE, including: engineering education should seek greater diversity, instructors and curriculum designers should utilize more effective, interactive teaching methods, and technical curricula should be taught while considering the broader implications of technology. In considering other reports that have proposed engineering education changes (from WWII until the present), the report notes that,

> …none of these reports was truly revolutionary. To a great extent, they described and reinforced unchanging principles that are basic to engineering education. It is startling to read them and recognize the consistency of many of their themes across the decades:
>
> * the need for strong grounding in the fundamentals of mathematics and the physical and engineering sciences;
> * the importance of design and laboratory experimentation;
> * a call for more attention to the development of communication and social skills in engineers;
> * the need for integration of social and economic studies and liberal arts into the curriculum;
> * the need to prepare students for career-long learning.
>
> The various reports differ mainly in the relative weight accorded to these themes.

One of the most significant outcomes of the above reports is ABET's "Engineering Criteria 2000" (EC 2000) which is the new standard against which engineering schools are measured for accreditation purposes. This new standard incorporates many of the themes of the earlier appeals for a stronger emphasis on math and science, with the recent emphases on design, diversity, and practical experience. Perhaps the most representative of the new standard are the 11 program outcomes referred to as "Criterion 3, a-k:"

> Engineering programs must demonstrate that their graduates have:
>
> (a) an ability to apply knowledge of mathematics, science, and engineering
> (b) an ability to design and conduct experiments, as well as to analyze and interpret data
> (c) an ability to design a system, component, or process to meet desired needs
> (d) an ability to function on multi-disciplinary teams
> (e) an ability to identify, formulate, and solve engineering problems
> (f) an understanding of professional and ethical responsibility
> (g) an ability to communicate effectively
> (h) the broad education necessary to understand the impact of engineering solutions in a global and societal context
> (i) a recognition of the need for, and an ability to engage in life-long learning
> (j) a knowledge of contemporary issues
> (k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice. [Engi, 97]

Like Terman and his contemporaries after World War II, ABET, through this set of criteria, is advocating that engineers have a good understanding of math and science, but the words used to describe this are application-focused rather theory-focused. For example criterion 3a states that graduating students should be able to "apply" math and science. The "Grinter Report" recommends that schools strengthen their "work in the basic sciences" and include "engineering sciences, taught with full use of the basic sciences." The "Grinter Report" advocated that engineering education move toward the science of engineering while EC 2000 is worded to affect changes which will refocus engineering education on the application of science. EC 2000 uses language like *apply*, *design*, *work*, *understand*, *communicate*, and *use tools* to describe the desired outcomes of an engineering education.

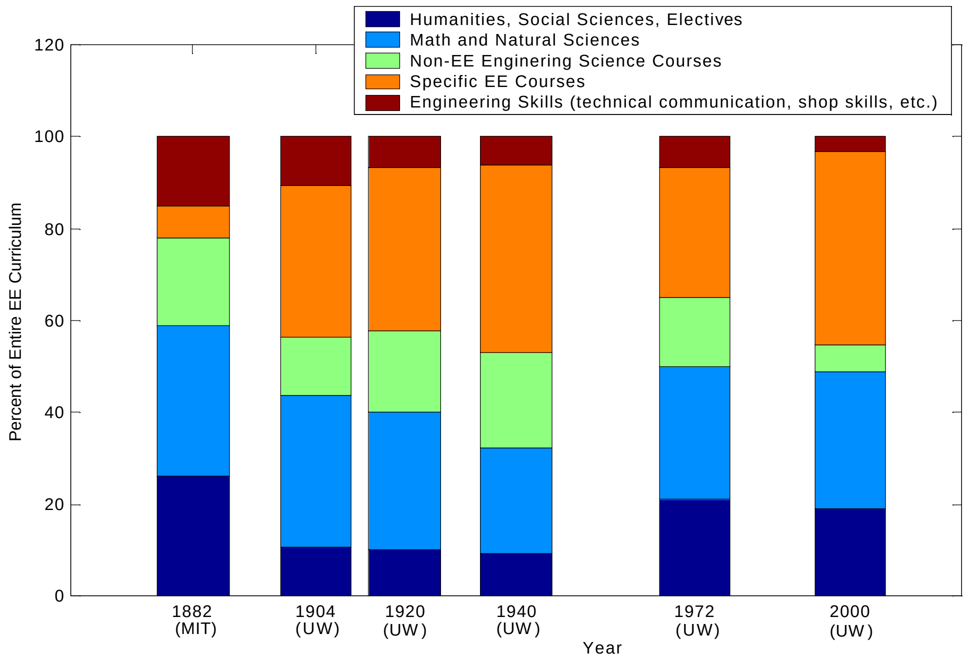


Figure 2.2 – Comparison of the content in EE curricula between 1882 and 2000

Figure 2.2 above illustrates how the present changes in EE curriculum fit into their historical context. Although this figure does not show dramatic changes in EE curriculum, some changes are worth noting. A steady increase in EE specific courses is evident between 1882 and 1940. In 1972 credits are shifted away from specific EE courses and then in 2000 these credits are shifted back. The 1972 proportion reflects a shift of credits from EE specific courses to the humanities and electives (many of which could be used for EE, math, or science courses according to the 1972 and 2000 catalogs) and to required math and natural sciences. The shift seems to be a result of the renewed emphasis on math and science after World War II. In 2000, many of the Non-EE engineering science credits are shifted to EE credits, most likely in response to the renewed emphasis on practical design skills. Another noticeable trend is the steady decline in the number of required "engineering skills" credits. This reflects the fact that early EE curricula included substantial portions of “shop” and “drafting” courses, whereas many contemporary engineering skills (such as the use of computer software) are incorporated into existing EE courses.

As EE educators seek to implement the changes recently advocated by ABET, ASEE, NSF, and NRC, it is important to understand why these changes are occurring and what historical events have led to the present state of EE education. If we carefully look at the structure of EE curricula in the past, including the first programs which were heavily rooted in Physics, the pre-World War II programs which were focused on EE applications, and the science-focused post-World War II programs, we may be able to avoid repeating past mistakes and improve on the high standard of electrical engineering education that the US has sustained through the past 120 years.

> “The principles of engineering design, leading to the manufacturing and construction process, should be given a more central role in undergraduate curricula.”
>
> from ASEE, *A National Action Agenda for Engineering Education*, 1987

3 Capstone Design and its Application in the Power Systems Engineering Curriculum

One of the eight essential program criterion outlined in EC 2000, is the “Professional Component,” under which engineering schools are required to engage engineering students in a “major design experience” [Engi, 97]. According to this criterion, “Students must be prepared for engineering practice through the curriculum culminating in a major design experience based on the knowledge and skills acquired in earlier coursework and incorporating engineering standards and realistic constraints that include most of the following considerations: economic; environmental; sustainability; manufacturability; ethical; health and safety; social; and political” [Engi, 97]. As mentioned in Chapter 1, the capstone requirement first appeared in ABET requirements in the late 1980s in order to meet the demand from industry for more design education in engineering curricula. EC 2000 reaffirms this requirement and more clearly defines what must be included in a capstone course. The fact that there is an ongoing demand for the teaching of design skills in undergraduate education is illustrated by the following abstract from a recent paper in the *Journal of Engineering Education* written by a representative of industry:

> “US industries are being beaten to the marketplace by foreign competition with a better quality product. What industry needs is clear: engineering graduates with better design experience. American engineering schools respond to this need by producing great scientists but mediocre engineers. More priority must be given to developing engineers rather than research scientists if the schools are serious about meeting the needs of American industry. This will require a major restructuring in most engineering faculty and administrations in terms of attitudes and priorities. This will not be a major restructuring of current engineering curricula, but rather, more open-ended problems inserted into the engineering science courses with frequent and spirited discussions of the design process. The tools of design can be woven into existing curriculum courses. The design experience must occur all four years and be capped off in the senior year with a "capstone" design course(s).” [Nicholai, 1998]

In light of this, this chapter will look at the rationale behind the use of capstone design courses in engineering curricula, the characteristics of effective capstone courses, and how these concepts relate to power systems education.

3.1 Rationale Behind Capstone Design

Capstone design courses are one of the means by which engineering schools can give their students preparation for practical engineering design work. Many engineering schools encourage their students to gain practical experience through a co-op or internship with an engineering company. Although this a good way for students to get some exposure to the engineering work environment, students rarely get direct instruction in the design process in this context. A capstone project, on the other hand, gives students an opportunity to learn practical design skills while also utilizing engineering science content learned earlier in the curriculum to produce a quasi-realistic design.

Although engineering students usually get extensive exposure to engineering science during traditional coursework, most engineering curricula include very little material on the design process despite the fact that research indicates that instruction in design can be helpful. One study of engineering designers showed that successful designers have a clear, methodical, yet flexible method. This authors of this study recommend that, “methodical approaches and tools should be integrated stepwise during the designer’s education” [Fric, 96]. Another study showed that students who read a text about the design process before performing a design task approached the design task with greater sophistication when compared with students who did not read the design text [Atma, 96]. Since reading a simple textbook can help students in the design process and good designers use methodical procedures, it is believed that comprehensive, interactive instruction in the effective design techniques in the context of a project-base engineering courses will help students to achieve greater success in industry. Although some argue that design education should be integrated throughout the engineering curriculum [Took, 92], the capstone course is a convenient venue for direct instruction on the design process.

Teaching the design process through a project-based course at the end of an engineering program has a number of benefits for the long-term retention of prerequisite material. If the design project requires the use of math and science material from prior courses it can serve to solidify the student’s understanding of these topics. Research on memory has shown that the more frequently a concept is revisited, the more solidly the information is embedded into the learner's mind [Ande, 95a]. Also, the capstone course can be an effective means to adding meaning to math and science material learned in prerequisite courses. As the design project forces students to revisit material from prerequisite courses, they are more likely to remember this material because its relevance to real-world design (meaning) is more evident. Meaningful information has been shown to be far more persistent than raw details. Anderson writes, "Because memory for meaning is longer lasting than memory for details, individuals can improve their memories by converting meaningless to-be-remembered information into a more meaningful form" [Ande, 95b]. The capstone design course is an opportunity for a student to re-learn material from prerequisite courses in a way that will likely be more persistent in his or her memory.

Another benefit of capstone design courses is that they can give students early exposure to problems that occur in a real world design situations. Bond, a professor at New Mexico Tech, identifies several specific challenges that capstone projects can bring out that are difficult to deal with in traditional engineering courses. According to Bond, "The capstone design course is not just about finding a technical solution to a particular problem. It is about problem/project definition, project planning, design selection and optimization, team building, communication, presentation skills, interpersonal skills, meeting skills, and conflict resolution" [Bond, 95]. These issues can be dealt with more effectively in a capstone design course than in a detailed engineering science course. Many capstone design courses are teamwork-based, giving students an opportunity to experience the advantages and disadvantages of team design work. One study on students doing design work in teams showed that teamwork leads to "a better clarification of the task," "the creation of a greater variety of solution principles," and "a more intensive analysis of the solutions presented" [Ehrl, 97]. This study also identifies several aspects of teamwork that can detract from an effective design process. Dominant team members often do not allow slower or more reserved team members to express ideas, substantially reducing the benefits of teamwork. This study showed that when teams were systematically supervised through the design process many of the disadvantages of teamwork did not adversely affect the design process [Ehrl, 97].

Given that design is an important part of "real-world" engineering work, and that teaching design through capstone courses can help improve student design skills, it seems likely that students who learn effective design skills while they have the supervision and instruction available in an academic setting will be more effective engineers as they bring these skills with them to industry.

3.2 Characteristics of Effective Capstone Courses

Many have undertaken to present various approaches to the capstone design course in the literature. Some advocate an individualized approach where students work independently on a project, whereas others advocate performing larger projects in multi-disciplinary teams. Some projects integrate a wide range of non-technical factors, whereas others are strictly technical. The recent changes in ABET requirements and industry expectations are encouraging universities to experiment with capstone courses which integrate a wider range of technical and non-technical factors, force students to work in a team environment and to spend substantial effort on the communication of project results.

One study comparing two different methods of conducting a capstone design course concluded that the following lead to more effective learning in the context of a capstone course: “increasing the number of formal class presentations, using student-led discussions to present sections of the case study materials, and incorporating peer-based review as a component of the formal course evaluations" [Neum, 98]. This professor argues that the peer reviews were a difficult part of engineering work that students are usually not prepared for in traditional education programs.

Many educators and industry leaders are currently recommending that engineering design be taught in a social context. This is clearly reflected in the ABET requirement that the “economic; environmental; sustainability; manufacturability; ethical; health and safety; social; and political” factors be considered in design curricula. This has been echoed by members of both academia and industry in the literature. A professor at New England Inst. of Tech. argues that, “Engineers should understand the context in which they are designing, and the social, cultural, and political aspects of their work, as well as the technical and business aspects. If engineering graduates are to be good designers as they advance their careers, then those of us who are teaching them design need to introduce them to a broader spectrum of issues in the context of their engineering design experiences as undergraduates.” [Newc, 97] A vice president of Northern Telecom, Inc. argues that, “We need to shift away from the trend toward simply collecting more and more specialized information and emphasize instead the evaluation of more broadly based knowledge and its implications to our society's needs." [Took, 92]. Although it may be difficult for some professors to integrate non-technical issues into a design course, there are good examples of ways to do this systematically. Vanderburg, a professor at University of Toronto, created a measuring tool for sustainability that was integrated into the engineering curriculum at that university. This professor recommended that such a tool be used in feedback loop to adjust a design according its impact on society [Vand, 99].

Arguably, the most important parts of a design course is the actual design problem which students work on. One professor points out that since students in engineering courses are expected to spend considerably more time learning outside the classroom then inside the classroom, the instructor should spend considerable effort ensuring that the problems and projects that students work on outside of class lead to quality learning [Hagl, 99]. Since engineering students often spend more time on capstone courses when compared to other courses, the instructor should ensure that the project or projects emphasize the goals of the course and the engineering program.

3.3 Teaching Power Systems Design

Most capstone projects are essentially the design and implementation of a new device to meet a given need. In Electrical Engineering, students are often asked to design and build a moderately complex electrical circuit to perform a given function. The project is almost always the design of a completely new product. On the other hand, electrical power systems are inherently large and old. Power systems are designed and constructed to last a long time, often 50 years or more. Therefore, design within the context of a power system is necessarily distinct from the design of a new electrical device. In order to teach power systems design (usually referred to as power systems planning), one must teach how to optimally integrate new components into a large, old system. This is particularly challenging because the existing system is the result of numerous sequential, possibly sub-optimal redesigns. Additionally, design prototyping is nearly impossible in power system design. A design must be almost entirely completed on paper before it can be implemented. Thus, simulation tools play a vital role in the power systems planning process.

Given these constraints, good power systems design projects must focus around an existing system and a means of simulation must be provided to the students. Whereas in a circuit design course, simulation is used as an intermediate means to the eventual product construction, the successful simulation of a power system design will most likely be the goal of the design process in an academic setting. Power system design projects should require students to compare infrastructure change alternatives with operation change alternatives. It is quite common for a power engineer to compare a system-expansion design (such as the addition of a new transmission line) and with doing nothing, or changing the manner in which the system is operated. This is in contrast to many other EE disciplines where different design options usually emerge as different ways to build a device to meet a set of specifications.

Furthermore, in power system design, the non-technical impacts of technology are often more noticeable than in other disciplines of electrical engineering. For example, electrical deregulation is a fundamentally economic endeavor that contemporary power engineers must deal with extensively. As mentioned in the introduction, deregulation is having a dramatic affect on the daily lives of people on the West Coast of the US as the electricity market in California has allowed bulk electric prices to jump orders of magnitude higher than those before deregulation. Also, when a new transmission line, substation, or generator needs to be constructed it will have a substantial impact on the land and the people living near the new construction. The social and environmental impact of various means of electrical generation is a highly controversial subject that has technical, political, social, and economic consequences. The power engineer should carefully consider these consequences. If power system education programs are to prepare students for success in industry these issues should be dealt with at the undergraduate level. The capstone design course provides an excellent forum through which these issues can be dealt with.

It is believed that as university educators incorporate practical design skills into power systems engineering curricula in response to EC 2000, the capstone design course should be used as a means to integrate prerequisite engineering coursework and non-technical skills. The hope is that this will lead engineers to be better prepared for their work in industry. Power system design projects should be carefully crafted to force students to consider both the technical and non-technical consequences of a design. In a power systems capstone course students should be required to expend considerable effort communicating their design as well as completing the design. The design course should be used to give students substantial opportunity to learn about working with people in teams. In order to do this the capstone design course must be designed to meet the concluding advice of Bond: “The reward system must match the wanted behavior” [Bond, 1995].

4 A Transient Stability Design Project

In chapter 2 we assert that capstone design projects can be an effective vehicle by which the design process can be taught. We also claim that one of the most difficult and time consuming yet important parts of preparing a capstone course is designing the design project. Whereas some have conducted capstone courses allowing students freedom to choose their own design project, this is difficult and unrealistic in for power systems. In the power systems discipline, design projects are difficult to contrive quickly. Most power systems design projects (apart from the design of an entirely new system, which is rarely done in industry) must use an existing system. A model of an existing power system will need to be provided to the students by the instructor. The data for numerous real power systems are available, but these are generally far too large and complex to be of any practical use in the context of a one-quarter (or semester) design course. Another option is to use of a ready-made mini-power system such as the IEEE 30 bus or 118 bus test cases. This is a legitimate option for some design problems, but these systems often do not demonstrate characteristics that will challenge the students to use power systems analysis skills learned in prerequisite courses. Additionally, these cases are not very representative of modern power systems as they date from the 1960's. A third option for the instructor is to develop an entirely new power system for use in a capstone course. Unfortunately, developing a new power system for instructional use is difficult and time consuming. It is unlikely that a professor preparing for a capstone course will have the time required to design a new power system to match a set of desired characteristics for each course offering.

In response to this difficulty a transient stability design project has been designed which challenges students to evaluate the economic and socio-political effects of transmission limits on the Pacific Northwest to California transmission corridor due to machine dynamic characteristics. The design project forces students to carefully consider all of the factors recommended in ABET EC 2000 including environmental, sustainability, manufacturability, ethical, health and safety, social, and political impacts of changes in operation and infrastructure. This chapter will present in detail the power system and design problem that has been developed and discuss the results of its implementation in a capstone design course.

4.1 The Reduced WSCC System

The most obvious requirement for a power system design project is a power system model. The model for this project was created to reflect heavy summer conditions on the Western System Coordinating Council (WSCC) system as represented by the NERC Form 715 filing WSCC HS3SB [WSCC, 1998]. The following criteria were used to develop the power system data set:

1. The system should be relatively small so that it can be easily represented on a single page or computer screen and so that the analysis of the system is computationally and conceptually manageable, but not so small that the analysis is trivial.
2. The system power flow should be convergent for the base case and for all line outage contingencies.
3. A relatively small increase in Northwest to California transfer should cause a transient stability problem.
4. The system should, at least marginally, reflect the peak summer operation of the WSCC system.

The system was developed using the Power System Toolbox [Chow, 1997] for the MATLAB environment for simulation purposes. The system configuration was chosen by forming each of the major utility/generation areas in the WSCC area into a single generation bus. The resulting system is shown in Figure 4.1. Although the system is rather unrealistic because it has only one PQ (load) bus, it is quite useful for transient studies, since most methods of time-domain simulation simplify the system to eliminate PQ buses (see section 5.6.2). Since the bus-angles in southern California are near zero in the WSCC 98HS3SB case, the Southern California Edison (SCE) bus was set as the swing bus.

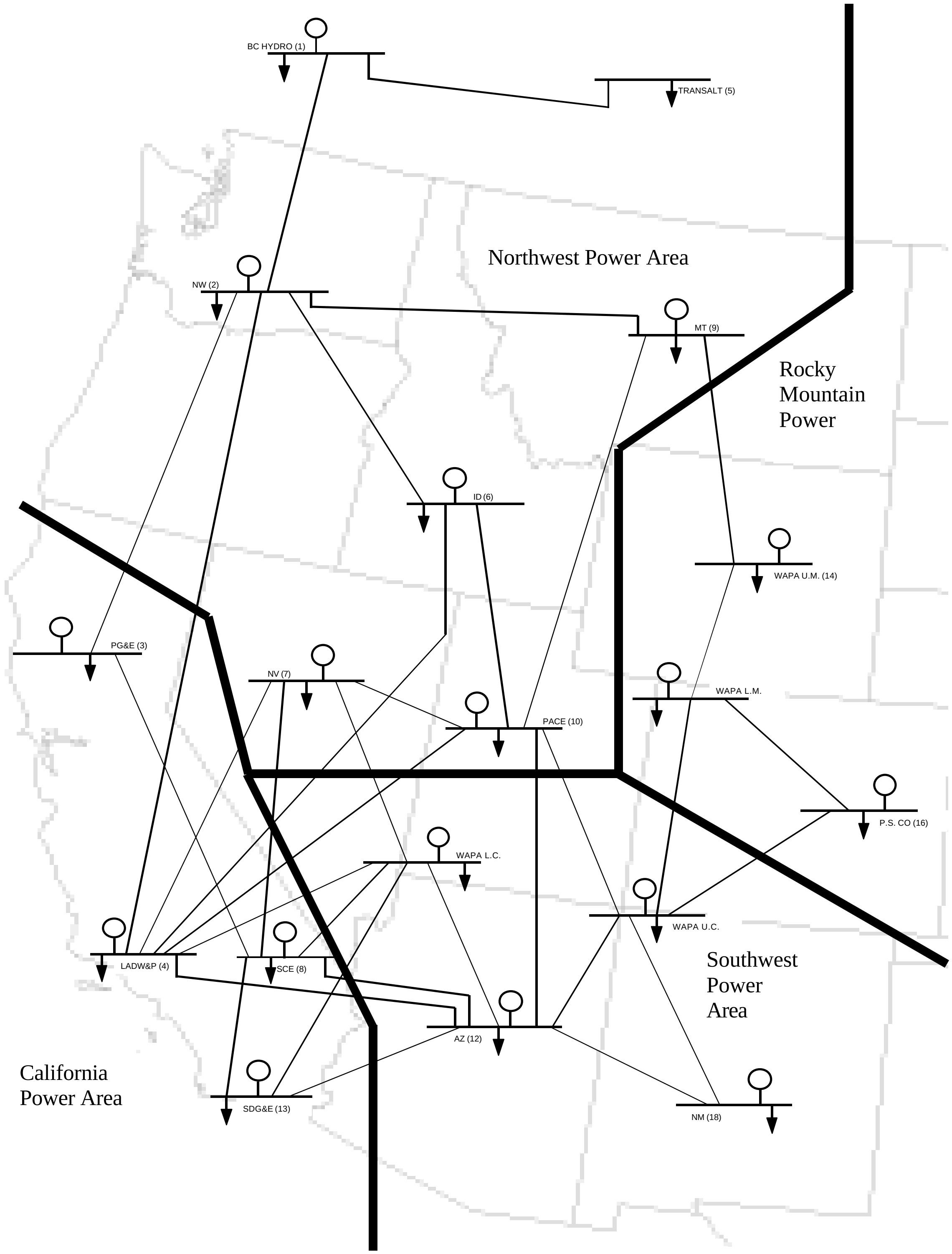


Figure 4.1 – The reduced WSCC power system

Once the system configuration had been set, the bus, line, and machine data were adjusted to meet criteria 1-4 above. This was done iteratively, primarily through trial and error. The area-loads were set to the sum of all the loads and shunts in each area. The generator power outputs were similarly set to the sum of the total generation in each respective area. The generator bus voltage magnitudes were set to the mean voltage in each area. The transmission line parameters were set by estimating the combined impedances of transmission lines connecting the two areas and setting the line impedance proportionally. Once all of the transmission line parameters had been set, the impedances were adjusted until the machine angles (from a power flow calculation) reflected the actual angles given in the model WSCC data. Once this had been done, machine parameters were selected to meet criterion 3. Initially the machine parameters were set by selecting three typical generators applying them to the different area-buses and setting the MVA-base of the machine to the approximate output of the machine. Once these initial parameters had been set, the machine parameters, the line impedances, and the generator outputs were adjusted until the system was marginally stable satisfying criterion 3. Further testing of the system showed that the system power-flow is convergent for all line outage contingencies satisfying criterion 2. Figure 4.2 shows the machine angles resulting from time domain simulation of the base case.

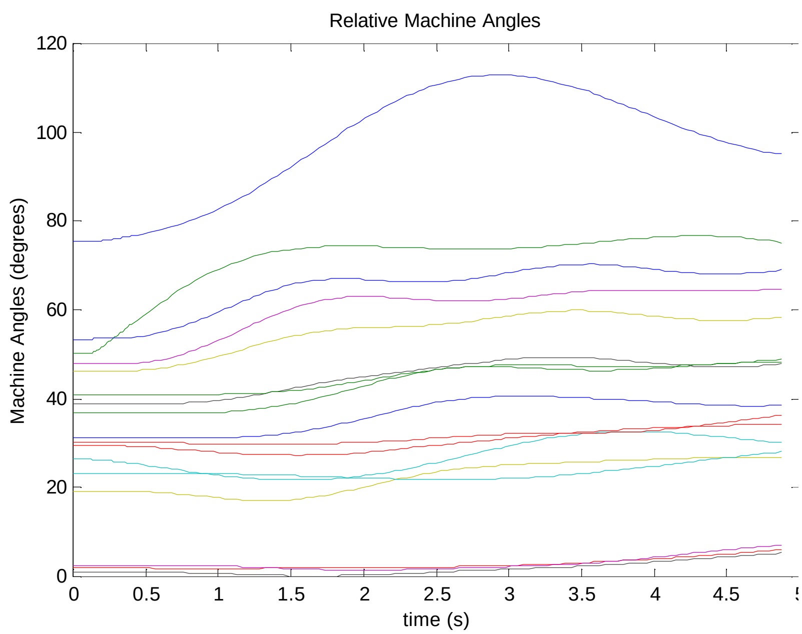


Figure 4.2 – Results of time-domain simulations of the reduced WSCC system

Table 4.1 – Bus parameters for the reduced WSCC system

Area Name	**Voltage Set Point (p.u.)**	**Real Generation (MW)**	**Real Load (MW)**	**Reactive Load (MVAr)**
BC Hydro	1.050	8860	6300	2800
Northwest	1.075	26868	2340	2600
PG&E	1.030	19577	21800	2200
LADWP	1.020	5512	5800	-3300
Trans Alt.	1.050	0	300	50
Idaho	1.060	3563	2800	700
Nevada	1.000	1637	4000	100
SCE (swing bus)	1.040	14540	19800	-1200
Montana	1.000	2793	1400	-800
PACE (UT)	1.040	4911	4300	900
WAPA L.C.	1.010	2215	0	24
Arizona	1.040	13867	12200	1800
SDG&E	1.030	2376	4400	-400
WAPA U.M.	1.010	212	80	40
WAPA L.M.	1.030	2600	2750	600
P.C. CO	1.000	3563	4700	700
WAPA U.C.	0.990	2696	600	400
New Mexico	1.020	2985	3200	400

Table 4.2 – Machine parameters for the reduced WSCC system. All values other than the MVA-base are in per unit. Per unit base = 100 MVA.

Area Name	**MVA Base**	X_L	X_d	X_d'	T_{d0}'	X_q	X_q'	T_{q0}'	**H**	**D**
BC Hydro	10780	0.0125	0.1000	0.03100	10.2	0.0690	0.0280	1.5	42	30
Northwest	36190	0.0199	0.1690	0.04570	9.4	0.1150	0.0450	1.5	31	40
PG&E	19910	0.0030	0.0296	0.00550	5.9	0.0286	0.0050	1.5	248	240
LADWP	4950	0.0017	0.0180	0.00285	4.1	0.0173	0.0025	1.5	300	40
Idaho	4290	0.0125	0.1000	0.03100	10.2	0.0690	0.0280	1.5	42	30
Nevada	1980	0.0125	0.1000	0.03100	10.2	0.0690	0.0280	1.5	42	30
SCE	12100	0.0017	0.0180	0.00285	4.1	0.0173	0.0025	1.5	100	60
Montana	3190	0.0125	0.1000	0.03100	10.2	0.0690	0.0280	1.5	42	30
PACE (UT)	5390	0.0017	0.0180	0.03100	10.2	0.0690	0.0280	1.5	100	60
WAPA L.C.	1320	0.0125	0.1000	0.03100	10.2	0.0690	0.0280	1.5	42	30
Arizona	13860	0.0030	0.0296	0.00550	5.9	0.0286	0.0050	1.5	248	240
SDG&E	2200	0.0125	0.1000	0.03100	10.2	0.0690	0.0280	1.5	42	30
WAPA U.M.	242	0.0125	0.1000	0.03100	10.2	0.0690	0.0280	1.5	42	30
WAPA L.M.	2310	0.0125	0.1000	0.03100	10.2	0.0690	0.0280	1.5	42	30
P.C. CO	3410	0.0125	0.1000	0.03100	10.2	0.0690	0.0280	1.5	42	30
WAPA U.C.	3300	0.0125	0.1000	0.03100	10.2	0.0690	0.0280	1.5	42	30
New Mexico	2860	0.0125	0.1000	0.03100	10.2	0.0690	0.0280	1.5	42	30

Table 4.3 – Line parameters for the reduced WSCC system. Per unit base = 100 MVA.

From Bus	To Bus	Line Resistance	Line Reactance	Shunt Susceptance
BC Hydro	Northwest	0.00221	0.02240	0.00020
Northwest	PG&E	0.00290	0.02890	0.00051
Northwest	LADWP	0.00286	0.02650	0.00025
Northwest	LADWP	0.00285	0.02840	0.00023
PG&E	SCE	0.00027	0.00230	0.00025
BC Hydro	Trans Alt.	0.00218	0.02250	0.00016
Northwest	Montana	0.00345	0.03710	0.00040
Northwest	Idaho	0.00363	0.03640	0.00060
Idaho	PACE (UT)	0.00232	0.02180	0.00025
Montana	PACE (UT)	0.00338	0.03580	0.00055
Montana	WAPA U.M.	0.00216	0.02300	0.00025
Nevada	LADWP	0.00340	0.03460	0.00041
Nevada	PACE (UT)	0.00208	0.02260	0.00019
Nevada	WAPA L.C.	0.00349	0.03630	0.00053
PACE (UT)	LADWP	0.00346	0.03650	0.00050
WAPA L.C.	LADWP	0.00224	0.02240	0.00018
WAPA L.C.	SCE	0.00225	0.02070	0.00023
WAPA L.C.	Arizona	0.00206	0.02290	0.00023
WAPA U.C.	Arizona	0.00340	0.03610	0.00055
WAPA U.M.	WAPA L.M.	0.00223	0.02220	0.00021
WAPA L.M.	P.C. CO	0.00218	0.02220	0.00017
WAPA L.M.	WAPA U.C.	0.00346	0.03430	0.00052
P.C. CO	WAPA U.C.	0.00336	0.03530	0.00050
PACE (UT)	WAPA U.C.	0.00358	0.03560	0.00051
WAPA U.C.	New Mexico	0.00353	0.03440	0.00047
LADWP	SCE	0.00222	0.02190	0.00018
LADWP	Arizona	0.00223	0.02190	0.00022
Arizona	New Mexico	0.00233	0.02230	0.00022
SCE	Arizona	0.00349	0.03420	0.00051
SCE	SDG&E	0.00225	0.02230	0.00027
Arizona	SDG&E	0.00230	0.02160	0.00022

Although the above system is useful for the purposes of this project, there are a number of factors which contribute to the fact that it is not a true representation of the WSCC system. Obviously the full WSCC system cannot be simplified to an 18 bus model and retain accuracy. In addition to the reduced size of the system, the machine models used for simulation purposes do not include exciters. This makes the system seem less stable than it actually is, and the analysis is generally only accurate for the first machine-angle swing. Also, the DC line from The Dalles in Oregon to Los Angeles is approximated by two AC lines in the reduced system. This will also decrease the stability of the system. Generally, the WSCC system is so complex that even professionals using detailed system models have difficulty simulating the dynamic behavior of the system [Kost, 1999]. Since our model has been simplified beyond the point where it could possibly simulate the true WSCC system, we did not attempt to replicate the exact operation of the WSCC system, but rather attempted to created a system that generally operates as a power system should and bears some resemblance to the WSCC system during times of high transfer. The system did meet this goal because the system becomes more stable when the power flow through the fault area is reduced, less stable when the power flow is increased, and more stable when additional transmission capacity is added to the system.

4.2 Hourly Demand Data for the Reduced WSCC System

In order to give students a taste of the amount of data that must be used to economically evaluate a design, a simple economic model for the WSCC system was developed. With this model students can better model the economic and socio-political impacts of stability constraints on the WSCC transmission system. In order to create an economic model of the system, we first created an hour-by-hour approximation of the system load for each of the four major areas in the WSCC system: California and Mexico (CA), the Southwest (SW), the Northwest (NW), and the Rocky Mountain (RM) power areas. The approximate boundaries of these areas are shown in Figure 4.1. Data from a 1999 WSCC report was used to generate the one-year load model [West, 99]. Table 4.4 shows the peak and mean loads for 1998 given in this report.

Table 4.4 – Peak and mean demand data for 1998 in the WSCC system [West, 99]

	Northwest		California		Southwest		Rocky Mountains	
Month	**Mean**	**Peak**	**Mean**	**Peak**	**Mean**	**Peak**	**Mean**	**Peak**
Jan	31769	55347	20348	36691	7419	13358	4272	7541
Feb	27342	50021	18740	35885	6778	12966	3755	7445
March	28935	50082	19413	35561	7103	12339	3943	7134
April	26667	46012	19461	37334	6799	13123	3712	6652
May	26771	43500	19820	33886	7463	14433	3771	6922
June	26456	45075	20756	41909	9111	18442	3861	7359
July	29357	49484	24848	49857	10786	20430	4331	7960
Aug.	28918	48690	26585	54586	10470	20429	4386	7975
Sept.	26730	47233	23013	55441	9140	18281	3871	7394
Oct.	27894	47252	20915	40667	7545	14041	3854	6700
Nov.	28893	50287	19548	35982	7061	12040	3986	7379
Dec.	33165	59972	21119	38304	7688	14106	4324	7740

Using this data the following steps were taken to develop a full-year set of demand data for 1998:

1. The mean demand data were fed into a cubic spline algorithm to interpolate the mean demand for every hour in 1998.
2. The peak demand numbers were similarly used to interpolate the peak demand for every hour in 1998.
3. A weekly power curve was created to show an approximate weekly load cycle.
4. The weekly curve was adjusted so that its mean was one and its maximum was such that when it was multiplied by the hourly mean demand the peak would be approximately equal to the peak given in the data.
5. Some randomness was added to the weekly curve to simulate the randomness of load changes.
6. Finally, randomized weekly curves were multiplied by the hourly mean demand.

This resulted in the data shown in Figure 4.3.

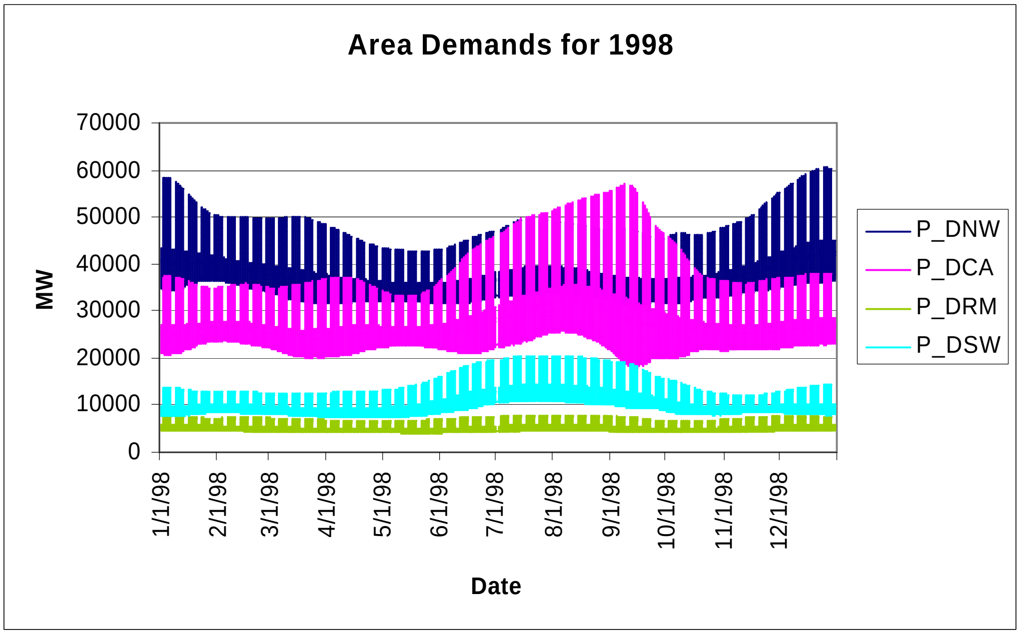


Figure 4.3 – Estimated hourly demand data for the Northwest (P_DNW), California (P_DCA), Rocky Mountain (P_DRM), and Southwest (P_DSW) power areas

4.3 The Design Problem

The goal in creating this design problem was to create a problem that gave students the opportunity to combine transient stability analysis with economic and social-political considerations. The actual text of the design problem as given to students in University of Washington EE 456 course during spring quarter 2000, is attached as appendix I. The problem asks each group of students to select from a list of organizations who are seeking an engineering team to represent them before a meeting of the fictional "Western States System Operators Coalition" (WSSOC). The WSSOC is supposedly working to create an 8-year plan for the transfer limit between the Northwest and California considering both the reliability and economics of the system. The WSSOC is asking that interested organizations submit written and oral reports outlining their recommendations for how the system should be upgraded and operated in the next 8 years. The students were asked to recommend changes to the current infrastructure and operating limits on behalf of the group that they represent. The groups were asked to give economic and political rationale for their recommendations in their reports. In order to complete this design project, students were asked to complete a technical, economic, and socio-political analysis of several design options (over the entire 8 year design period) and recommend what they considered to be the best option. In their report the students were asked to defend their recommendation based on technical and economic analysis and the interests of their client.

Due to the limited time available to the students for this project, several tools were developed to aid the students with the analysis. Several MATLAB tools were developed which work with the Power System Toolbox to help with power system analysis tasks, and an economic analysis spreadsheet (which was bundled with the hourly demand data described in section 4.2) was developed to help with economic calculations. In addition, the students were given approximate costs for transmission expansion and switching system upgrades. These monetary figures were used to compare alternatives which included either or both of infrastructure expansion and operating limit changes.

4.3.1 Economic Analysis Spreadsheet

The economic analysis spreadsheet was used to help students calculate the economic impact of changes in the Northwest to California transfer limits, based on transient stability analysis.

Essentially, the spreadsheet was designed to calculate the one year cost of congestion in the system given a year of hourly demand data and the transfer limit.

Several approximations were made to create a relatively simple means of performing this calculation. These approximations are based on common competitive market assumptions and assumptions about the West Coast power systems. Firstly, we assumed that all trades between the Northwest and California occur at a single price. This assumes that there is perfect competition and perfect price information. We also assume that transaction costs are negligible. With these assumptions we can lump the California power market and the northwest power market into large market participants with non-decreasing incremental cost (or supply) curves. We further assume that the supply curves are linear in order to simplify the problem. Observation of the actual California power market will quickly show that this assumption is inaccurate as price increases at a dramatically increasing rate when the total demand approaches the total available capacity. Nevertheless, this assumption simplifies the calculations substantially so we use the linear model. The two linear supply curves for the NW and CA areas can be described with:

$$IC_{NW} = a_{NW} + b_{NW} \cdot P_{G\_NW} \tag{4.1}$$

$$IC_{CA} = a_{CA} + b_{CA} \cdot P_{G\_CA} \tag{4.2}$$

where P_{G_AB} is the total generation in area AB, and *a* and *b* are scalars that define the incremental cost functions. Figure 4.4 shows the Northwest and California incremental costs with the *a* and *b* values selected for use in this project. For the sake of calculating the area generation outputs it was assumed that the market functions such that the incremental costs in the NW and CA areas are always equal. Thus:

$$a_{NW} + b_{NW} \cdot P_{G\_NW} = a_{CA} + b_{CA} \cdot P_{G\_CA} \tag{4.3}$$

Although this market model is simple, it is useful for the purposes of this project.

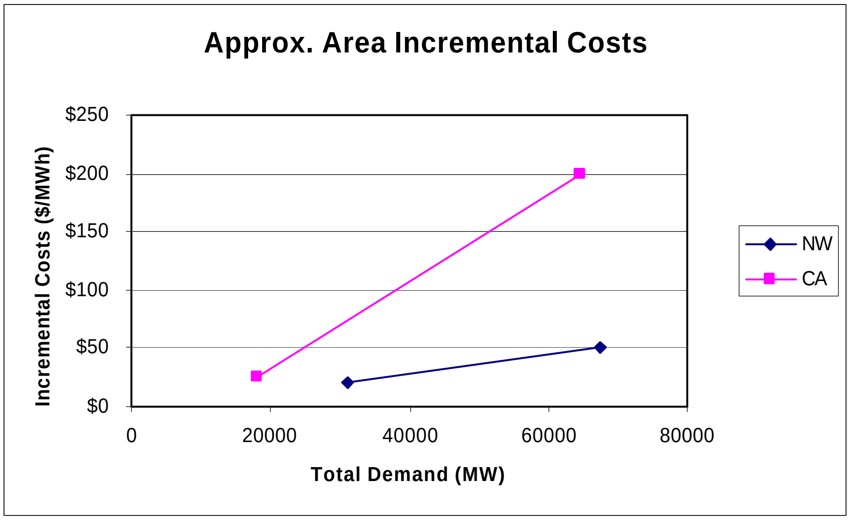


Figure 4.4 – Incremental costs used for the economic analysis spreadsheet

Secondly, it was assumed that the generation in both the other two areas (RM and SW) is directly proportional to the load at the current hour:

$$P_{G\_SW} = k_{SW} \cdot P_{D\_SW} \tag{4.4}$$

$$P_{G\_RM} = k_{RM} \cdot P_{D\_RM} \tag{4.5}$$

where k_{SW} and k_{RM} are scalars, and P_{D_SW} and P_{D_RM} are the power demand in the Southwest and Rocky Mountain areas. k_{SW} and k_{RM} were set using the P_G and P_D from the base case bus data of the reduced WSCC system. Additionally it was assumed that the total system generation was equal to the total system load (zero transmission losses):

$$\sum P_G = \sum P_D \tag{4.6}$$

$$\begin{aligned} &P_{G\_NW} + P_{G\_CA} + P_{G\_SW} + P_{G\_RM} = \\ &\quad P_{D\_NW} + P_{D\_CA} + P_{D\_SW} + P_{D\_RM} \end{aligned} \tag{4.7}$$

From the above the generation in NW was determined by solving for P_{G_CA} in eq. 4.3, substituting into eq. 4.7, and solving for P_{G_NW}:

$$P_{G\_NW} = \frac{a_{CA} - a_{NW} + b_{CA}(P_{D\_NW} + P_{D\_CA} + P_{D\_SW} + P_{D\_RM} - P_{G\_SW} - P_{G\_RM})}{b_{CA} + b_{NW}} \tag{4.8}$$

Similarly the generation in CA can be determined with:

$$P_{G\_CA} = \frac{a_{NW} - a_{CA} + b_{NW}(P_{D\_NW} + P_{D\_CA} + P_{D\_SW} + P_{D\_RM} - P_{G\_SW} - P_{G\_RM})}{b_{CA} + b_{NW}} \tag{4.9}$$

Equations 4.4, 4.5, 4.8, and 4.9 were used to calculate the unconstrained power generation at each hour. Also, assuming that the price of electricity is equal to the incremental cost in each area, eqs. 4.1 and 4.2 (which are equal if there are no transfer limits on the system) were used to calculate the price of electricity according to the market. From this the unconstrained cost of electricity was calculated for the entire NW/CA system for an entire year.

The above calculation is necessary to calculate the cost of congestion in this system. For the sake of the congestion calculation, the transfer from the northwest (T_{NW}) was defined as the sum of the total MW transfer outside of the NW area; thus:

$$T_{NW} = P_{G\_NW} - P_{L\_NW} \tag{4.10}$$

If the dynamics of the system require that T_{NW} be limited at a certain value ($T_{NW}^{\max}$) the system is considered to be congested and equation 4.3 will not hold. In the congested case P_{G_NW} will necessarily be:

$$P_{G\_NW} = P_{L\_NW} + T_{NW}^{\max} \tag{4.11}$$

The incremental costs will no longer determine the generation in the NW and CA areas and eqs. 4.1 and 4.2 will no longer be equal. There will be a difference between the unconstrained cost of electricity and the constrained cost of electricity. The difference between the constrained and the unconstrained cost is a measure of the market inefficiency [Chri, 2000], and is necessarily positive (if there is congestion) or zero (if there is no congestion).

The spreadsheet gives students the ability to view the cost of congestion for any year in the design period (1999-2008) given the calculated transient stability limit (TTC), and a safety margin. This gives a value for the available transfer capacity (ATC) which was defined as the difference between TTC and the chosen safety margin. The ATC was then used in the cost of congestion calculation. Figure 4.5 shows the economic calculations page of the spreadsheet.

Use This Page for Economic Calculations:					
	Blue-Text Cells Are Input Variables				
	Green-Text Cells are Calculated Results				
TrStab Limit (TTC) =	9782.00	Growth Percentage from 1998			
Safety Margin =	5000.00	NW	CA	RM	SW
ATC =	4782.00	11.72%	13.33%	24.79%	27.85%
Year =	2008				
Unconstrained NW/CA Cost =	$14,322,467,871				
Constrained NW/CA Cost =	$14,417,824,893				
Difference =	$95,357,022				

Figure 4.5 – Economic calculation page of the economic analysis spreadsheet

4.3.2 Power System Analysis Tools

In addition to the economic analysis tool above a few simple MATLAB tools to aid students with the Power Systems Toolbox were developed. Most significant of these is a tool which iteratively calculates the total transfer capacity (transfer defined as in equation 4.10) of the system based on the reaction of the system to a given sequence of events. With this program the algorithm shown in Figure 4.6 is used to calculate the TTC. During each iteration the stability is determined based on the angles of the generators at the end of a 12 second simulation. If the generator angles are substantially further apart at the end of the simulation than at the beginning of the simulation, the system is considered unstable. Otherwise the system is considered stable.

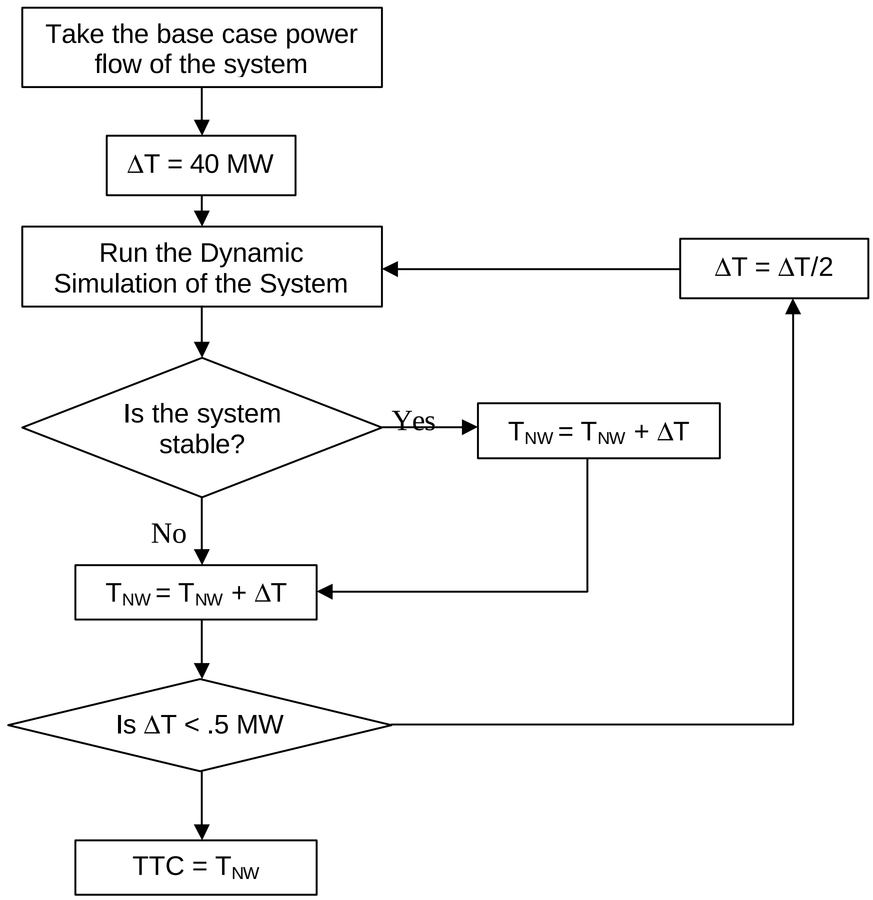


Figure 4.6 – Flow diagram of the TTC calculation program

4.4 Conclusions from the Implementation of the Transient Stability Design Project

The design problem and tools detailed in this chapter were used in the Spring of 1999 as the final project of a power systems capstone course at the University of Washington. Generally the project went well, but there are a number of things which could be done to improve the project for futures uses. Many of the tools described above were developed at the last minute before their use in the class, thus numerous bugs and terminology confusions were discovered as they were used for the project. Also, since much of the detailed analysis was done by the spreadsheet and the MATLAB scripts students were not required to think as carefully about the analysis process as they would have if they had developed the analysis tools on their own. It may be helpful in the future for students to initially develop a portion of the economic spreadsheet in order to better understand the economic analysis process. The full spreadsheet could be given after this initial assignment to simplify the complete analysis. Also, the Power System Toolbox time-domain simulation program does not give students a very wide range of easy-to-implement options for improving the system stability. It is fairly easy to reduce the time required to clear a fault (simulating the installation of a faster circuit breaker/relay system), but the PST does not support reclosing, and adding power electronic measures (such as a Power System Stabilizer) is a difficult process. Thus students were only able to add additional transmission capacity to the system or add high-speed switching systems to certain buses. The PST is also a set of text-based MATLAB programs which are rather difficult to learn and use. It would be helpful in the future to have an analysis tool that handles a wider range of design options and is easier to use.

Despite the above problems, the transient stability design project meets the criteria of ABET EC 2000 for a design project by combining technical analysis with non-technical analysis into the design process. Students were required to compare design alternatives and report their results. The fact that the project had some relationship to the real world also seemed to be helpful in motivating students.

5 A Power Systems Simulation Tool for Undergraduate Design Projects

As discussed in chapter three, simulation is an integral part of power system design in both educational and industrial contexts. Building physical power system models or prototypes is in most cases highly impractical. Thus, computer simulation has become the primary means of system analysis in power systems. As computers become faster and more available, simulation software is also improving in both performance and accessibility. Unfortunately, most industry focused software packages are too expensive and difficult to learn to be practical in an educational environment. On the other hand, many software packages developed for educational use are out of date and lack the computational sophistication needed to work on even pseudo-realistic problems. In order to deal with this problem a software package called "PowerViz" was developed which includes sufficient complexity to do many of the design problems one would encounter in a power systems design course but is designed to be easier to use than industrial packages. The overall goal of this component of our project was to create an integrated suite of software modules which will make the analysis of power systems simple enough that a small power system (~30 bus) can be repeatedly analyzed with minimal student time. It is our hope that this will allow students to expend minimal effort understanding the software and maximal effort solving power systems design problems. We sought to achieve this goal by making the means of user input simple and intuitive and the primary means of data output visual as opposed to numerical. In this chapter we will discuss the use of information technology in education, review several educational power systems simulation tools as presented in the literature and present the software package which has been developed for this project.

5.1 The Use of Information Technology in Education

Engineering educators throughout the world are increasingly using computer simulation programs and other computer-based teaching tools to teach engineering topics. Although the use of information technology (IT) does not guarantee an improved education, many studies have shown that careful use of IT can aid student learning [Kadi, 00]. After the analysis of 760 studies on the use of IT in education, Kadiyala and Crynes state that,

> Our review provides convincing evidence that information technologies can enhance learning when the pedagogy is sound and when there is good match of technology as a catalyst for improving learning in its environment. Educational technology has been shown to stimulate more interactive teaching, effective grouping of students, and cooperative learning. [Kadi, 00]

They also observe that "multimedia modules helped college students in engineering understand the concepts qualitatively and the importance of the concepts. However, they did not help students in generating examples of where these concepts are applicable." [Kadi, 00] There are numerous examples in the literature of how some form of computer software was used to improve a course [Lubk, 91], [Khan, 99]. One study of a variety of different types of technology-based education showed that the most useful types of technology that can be used to enhance undergraduate engineering education (based on a broad set of criteria), are CAD tools, computer math packages, computer simulation, and the use of computer based problems which is also known as anchored instruction [Bour, 95].

5.2 Review of Existing Educational Power Systems Software

Many power-system computation tools intended for educational use have been presented in the literature. From the early days of such software there has been an emphasis on using the graphical capabilities of the computer to help students understand problems better and to speed up the design and/or analysis process. In 1983 Salon presented a graphically-oriented software package used at Rensselaer Polytechnic Institute [Salo, 83]. This package uses computer graphics to help students understand topics in electrical energy, including electromagnetics, traveling waves, electric machinery, and power flow. The electromagnetic program shows students the electrical and magnetic field lines for types of electrical systems. The electric machinery program can be used to view the transient behavior of groups of machines. The power flow program displays the power flow by writing the calculated bus voltages and line currents to a one-line display. Salon points out that, "By having an interactive program, the students can interrogate the program, request various pieces of information, change input data, or repeat previous steps. By having graphics capability and an interactive means of communication with the terminal such as a light pen or a bit pad, the response time enormously sharpened." Similarly in 1986 a program was presented that sought to be interactive and flexible and to have an easily comprehensible graphics display [Lo, 86]. This program includes power flow, economic dispatch, and contingency analysis options. As in Salon's software, the program writes calculated results to an on-screen one-line diagram. Similarly, Wachal et al. [Wach, 84] and Yu et al. [Yu, 89] developed programs which perform power flow and transient calculations with some methods for graphical data entry and results displays. Unfortunately, to our knowledge, this program has not been maintained, or is not available to the public. One program presented in the literature (which was still in use in a University of Washington power systems analysis course in 2000) requires the user to input data and view results via a text-only MS-DOS screen [Glov, 88].

In the early 1990's several menu driven software packages were developed for use with personal computers. Most of these are reasonably complex integrated analysis packages including economic, power flow, contingency, fault, and transient analysis tools. One program, called PSADE, includes many of the features of modern analysis programs including power flow, optimal power flow, transient stability, and short-circuit analysis [Huan, 91] and supports the display and analysis of large power systems. Similarly, Hatziadoniu et al [Hatz, 91] and Chowdhury and Clark [Chow, 92], present programs which integrate a variety of analysis packages into a unified MS-DOS-based program. While these programs do give the user fairly simple methods for performing power system analysis tasks, the calculated results (other than transient analysis) are displayed numerically rather than through visualization. The program presented by Hatzladoniu et. al [Hatz, 91] does give the user some visual feedback by using arrows on the one-line to indicate the direction of power flow, but the power flow magnitude must be viewed numerically.

More recently, numerous Microsoft Windows analysis tools have been developed with increased usability and visualization. Li and Shahidehpour [Li, 93] developed a program with a variety of analysis tools (including unit commitment and state estimation), but still show calculated power flow results in numerical format on the one-line. This program is not useful for our purposes as it does not include a transient stability analysis package. In 1995 Overbye et al. presented an education-focused simulation tool which uses visualization to present calculated results [Over, 95]. The program, now known as Power World, presented line flow magnitudes using a mini pie-chart for each line which shows the flow limit and the calculated power flow. The program also includes several tools for graphically analyzing power transfer between areas.

More recent editions of the program show power flow magnitudes and directions through moving arrows of varied sizes on each transmission line [Over, 96]. The program also has methods for graphically displaying voltage profiles and several types of economic data [Over, 00]. Presently, Power World does not include a transient stability analysis package. Despite its advantages the full version of the program is quite expensive and the evaluation/education version only allows the user to simulate 12 buses. It is our view that such small systems do not give the user a sufficiently complete understanding of the real complexity of a power system. In 1998, Yang and Anderson presented a program which touted using visualization to show results and was designed to have a short learning curve. Unfortunately the program still presents calculation results numerically as opposed to graphically and does not include a transient analysis tool [Yang, 98]. Similarly, a program was presented in 1999 which does include a transient analysis tool and uses graphical displays but does not present power flow results visually [Shin, 99]. While this program is fairly easy to use, the transient stability tool uses a simple voltage behind transient reactance machine model. Our tests have shown that this machine model, when applied to the WSCC system described in chapter 4, does not produce sufficiently accurate results. Another difficulty with most all of the above programs is that they are not readily available. While a demo version of Power World can be obtained from the web site, it is limited to simulating 12 bus systems. Similarly a demo version of Yang and Anderson's program is available, but it can only simulate up to 16 buses. The other programs are not publicly available to our knowledge.

5.3 Visualization and Power Systems Software

As the computational power and graphical abilities of computers increases rapidly, the focus of power systems research is at least partially shifting from efficient means of producing power systems data to effective means of communicating available data. In general power system operators and engineers are more interested in a qualitative understanding of power system data than in the exact numerical data [deAz, 96]. Also, in emergency operation situations, as in most iterative design situations, it is more important that engineers be able to process data and locate problems with speed than it is for them to process data with perfect numerical accuracy. Research has shown that people generally process graphical information with greater speed, whereas they process textual information with greater accuracy [Sand, 93].

Visualization has been applied to several different types of power systems calculations in the literature, but the major portion of the research in this field has been focused on the representation of power flow results. Traditionally, full-graphics power system displays in both analysis and EMS software show the system one line with various numerical values written on the display. As mentioned above, this is good for numeric accuracy, but does not lend to high speed comprehension of data. Several approaches to showing line-flow and bus voltages have been presented in the literature. In 1992 Mahadev and Christie presented software which shows line flows by the thickness of a transmission line, and bus voltages as the height of a color difference in the bus-node (like in a thermometer) [Maha, 92]. Users using this method of visualization generally came to more speedy conclusions about the power system, but their answers were less accurate if the question required the user to recognize small changes in bus voltages or line flows [Maha, 95]. This software also used a nodal view of the power system instead of the traditional one-line view which more closely matches the geographical layout of the power system. In the nodal view buses are shown as circles and transmission lines are shown as straight lines between the circular buses. de Azevedo, de Souza, and Feijó demonstrated that this nodal view of the power system allowed for greater retention of the network structure than the traditional bus/one-line view [deAz, 96]. Alternatively, some have proposed the use of color scales and contour plots to describe bus voltages [Mitz, 97, Webe, 00]. The difficulty with contour plots is that they generally fill the entire display area with color information that may be visually distracting or interfere with other information when the user is not explicitly interested in bus voltages. Other methods have been proposed in the literature for describing line flows also. de Azevedo, de Souza, and Feijó use a method similar to that of Mahadev and Christie by indicating power flow magnitude with transmission line width [deAz, 96]. Overbye et. al used animated arrows on each transmission line to show line flow magnitude and directions [Over, 95].

Different methods for the visualization of time domain events (such as those simulated to evaluate the transient stability of a system) have also been presented in the literature. The traditional method of displaying the results of transient stability calculations is to show machine angles or other machine or bus properties vs. time. This has the advantage of being context intuitive since engineers are fairly accustomed to looking at time domain graphs. The disadvantage of this approach is that it is difficult to immediately see which curves belong to which machines. Some professional tools solve this problem by marking each machine curve with a numerical, name, number, or code corresponding to a machine in the system. If the user is very familiar with the power system being analyzed this notation is quite effective, because the user will have a mental link between the machine code and its geographical location. Since users process textual information more slowly than graphical information, users who are not familiar with the power system may have difficulty quickly relating a machine curve to its respective geographical location on the system one-line. Since students working on problems like the one described in chapter two need to know where problems occur in order to make design decisions it is important that they be able to relate a machine curve with its respective machine location on the one-line. Another disadvantage of the time domain curve method is that the transient stability phenomenon is often difficult to conceptualize for novices and time-domain graphs do not necessarily lead to an intuitive understanding of what is actually occurring in and between the machines.

In order to solve the second problem above Gronquist et. al use animated arrows on a circular angle graph to show the machine angles and rotational velocities in all instants of time. The authors claim that this method effectively demonstrates the strength or weaknesses of electrical couplings between generators and the islanding concept. The problem with this representation is that it is virtually impossible for a user to relate the arrows to the geographic location of the generators. The method may be useful for understanding the concept of islanding or stability, but it does not seem to give much help to those who need to use this information to make appropriately located design changes to a system. Kobayashi, Okamoto, and Sekine developed an animated visualization method which puts all of the buses a graph where the x location corresponds to the bus's x-axis location on the one-line, and the y location corresponds to the relative machine angle of the bus. The transmission lines are shown on this display as boxes between the buses with widths relative to the power flowing through the line. This display has the advantage that it can demonstrate oscillations over time, and that it is somewhat easier to relate the buses as shown on the animated display with their respective geographical locations relative to their actual geographical location. This display allows the user to see both the power and the machine angle differences flowing through each line. This can be useful information when doing transient stability analysis, and is not generally available in the time-domain graph method. The problem with this display method is that it is still difficult to relate the virtual animated bus on the x–d plane with its geographic location on the one-line.

5.4 PowerViz Design Criteria

The primary goal in creating this program was to create an integrated suite of software modules which make the analysis of power systems simple enough that a small or medium sized student design problem (~30 bus) can be repeatedly analyzed and changed with minimal student time. By doing this we hope to minimize the time and effort that students expend in understanding the software, permitting students to spend most of their time solving power systems design problems.

5.4.1 General requirements

The following general requirements were used to design this software:

Minimize interface complexity. The interface is should not include unnecessary complexity. The interface of the individual modules should be similar enough that once familiarity is achieved with one module, familiarity with other modules will require minimal effort.

Reasonable level of computational power and precision. The program should include sufficient computational complexity to allow the user to have a high degree of confidence in the analysis results. The program should require enough input from the user to facilitate this level of computational complexity.

Consistent data format. The program should use only one input data format (such as a text file or database) so that the user does not need to rewrite the data in a new format for each module.

Graphical data input and modification. Each module should allow the user to adjust the input data in ways that would normally be done in the design process. The program should allow the user to add or subtract components from the graphical user interface in ways that are intuitive. Programs should allow for batch creation and interactive update of the input data. The updating options should be interactively updateable.

Instantaneous results to system modification. When the user changes input data graphically the program should calculate and display results without additional user interaction.

Graphical Results. Each module should show computation results with an intuitive graphical representation in addition to allowing the user to easily obtain numerical results when required.

5.4.2 Module specific requirements

In its present state the program has three main modules. The first is a power flow analysis module which calculates the power flow using a simple Newton-Raphson method, and displays the line flow and bus voltage results visually. The second is an N-1 contingency analysis program which calculates the power flow of the system for each transmission outage. The maximum flows in each line are displayed, and the user is given the option of quickly jumping to the power flow for any of the possible line outages. The third module is a time domain simulator which can be used to evaluate the time-domain stability of a program given a sequence of events.

5.4.3 Power flow analysis requirements

This module was written to closely match the visual interface of the "WinViz" program developed by Mahadev and Christie [Maha, 92]. The amplitude of the power-flow through a transmission line is indicated by the width of an arrow between two buses. The line capacity is indicated by a box which encloses the power flow arrow. Per-unit bus voltages are shown graphically at each bus. The module allows users to easily remove a transmission line to show the impact of a system outage and allows users to change the transmission line parameters with minimal effort and show calculated results instantaneously.

5.4.4 Contingency analysis requirements

This module completes an automatic "N-1 contingency analysis" in order to find the impact of all line outages on the overall system. This module was designed to indicate clearly which lines are contingency problems and allow the user to see the results of the loss of this line by clicking on this line and displaying the modified power flow. Contingency analysis is a menu option from the power flow package. This user interface for the contingency module was designed based the visualization methods presented by Mahadev and Christie in [Maha, 94].

5.4.5 Transient stability analysis requirements

This module was designed to use standard, existing algorithms for stability analysis to calculate the transient response of a system and describe the results graphically on the one-line representation of the system similar to the other modules. The user interface is designed to clearly indicate where there are system stability problems, and allow the user to easily change system components without editing the data file.

5.5 The PowerViz User Interface.

While PowerViz was developed using the general design criteria above, most of the detailed design was done during the development process. This allowed us to test different approaches to each user interface issue before choosing a method that we felt best depicts the power system. The program uses "task adaptive visualization" [Maha, 96] so that the user interface changes depending on the current type of analysis that the user is working on. The resulting program has three primary "modes" each with slightly different visualization schemes. The user can change between modes by selecting the mode from a drop-down box on the tool-bar or by selecting an analysis "tool" from the Tools menu. The three modes are discussed in more detail below.

5.5.1 Power flow mode

In the power flow mode the user can visually and numerically view power flow results, add and remove transmission lines, view the results of line outages, and edit the system data. The basic power flow mode user interface for the WSCC system depicted in figure 4.1 is shown in figure 5.1. Buses are represented by boxes and transmission lines by arrows as discussed in section 5.4.3. In this representation the thickness of the line indicates the amplitude of the power flow and the direction of the arrow indicates the power flow direction as done in WinViz [Maha, 92]. The gray box around the transmission lines indicates the maximum power flow allowable through the line. Lines which have exceeded their rated limit are indicated by changing the color of the arrow to yellow. The effect of a line outage can be viewed instantaneously by double clicking on a line. This removes the line from service. The program automatically recalculates the power flow and updates the bus voltage and line flow displays accordingly. Although calculated results are not written directly on the one-line display, bus voltages and line flows can easily be viewed in the status bar by dragging the mouse over a bus or line. The text in the status bar at the bottom left corner of the screen shows different numerical results based on the mouse location. In addition the user can view the calculated power flow results in tabular format by selecting View | Flow Log from the menu. The flow log for the WSCC system is attached as appendix II.

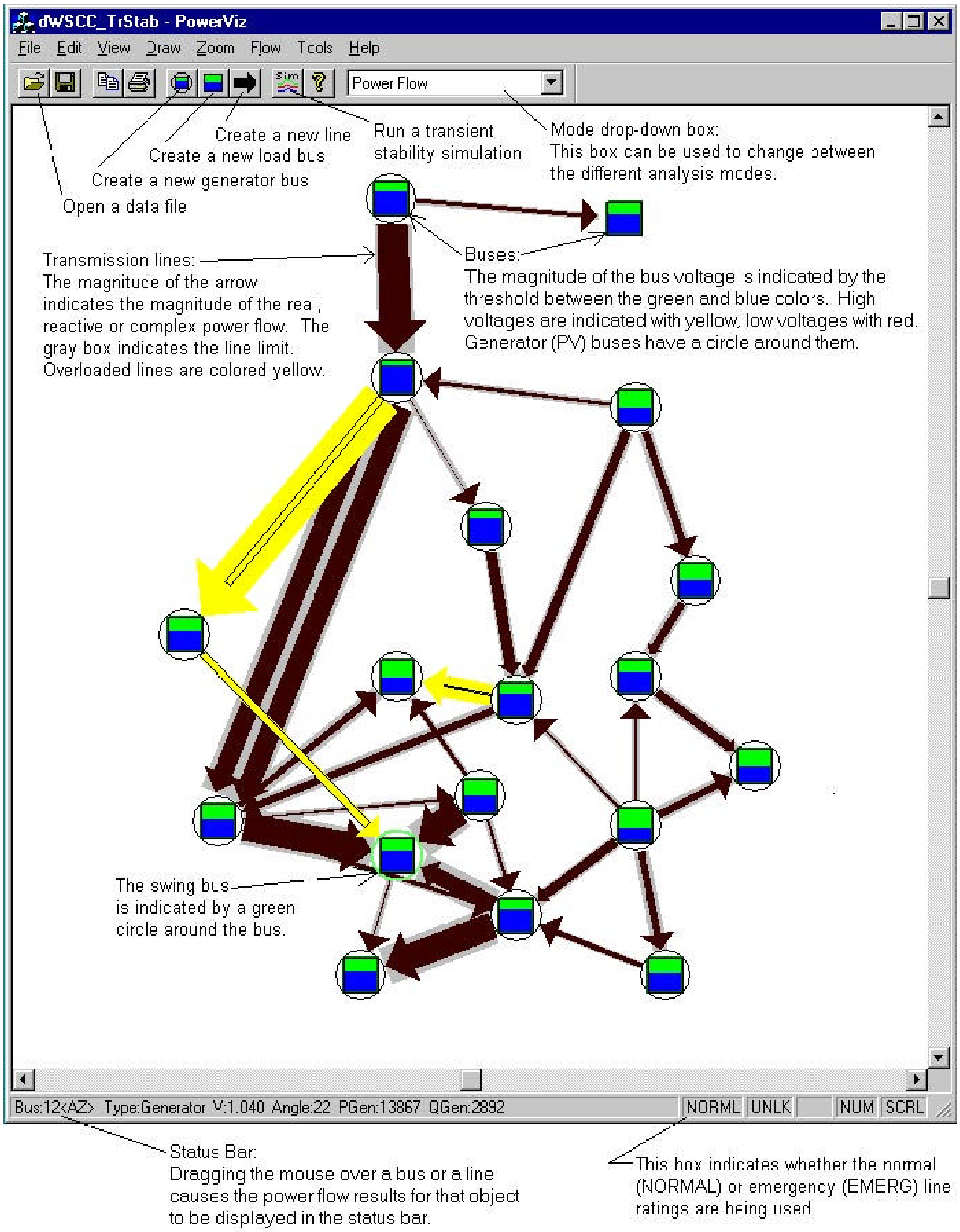


Figure 5.1 – Power flow mode user interface diagram

The power flow mode is designed to show the results of a change in the system virtually instantaneously. The effect of a change in the bus or line data can be viewed by simply changing the data through a set of dialog boxes. The power flow is automatically recalculated when the input data changes. Right clicking on a bus or a line brings up the respective data input dialog box. The load bus dialog is shown in figure 5.2. The input data boxes are shown alongside a one-line representation of the bus in order to help students understand the meaning of each piece of required data. The user can edit the reactive power of the load at the bus using the MVAr text box or by setting the power factor. When the user chooses “OK” the power flow is recalculated, and the display is updated. In this way the user can quickly see the effect of a change in the bus data.

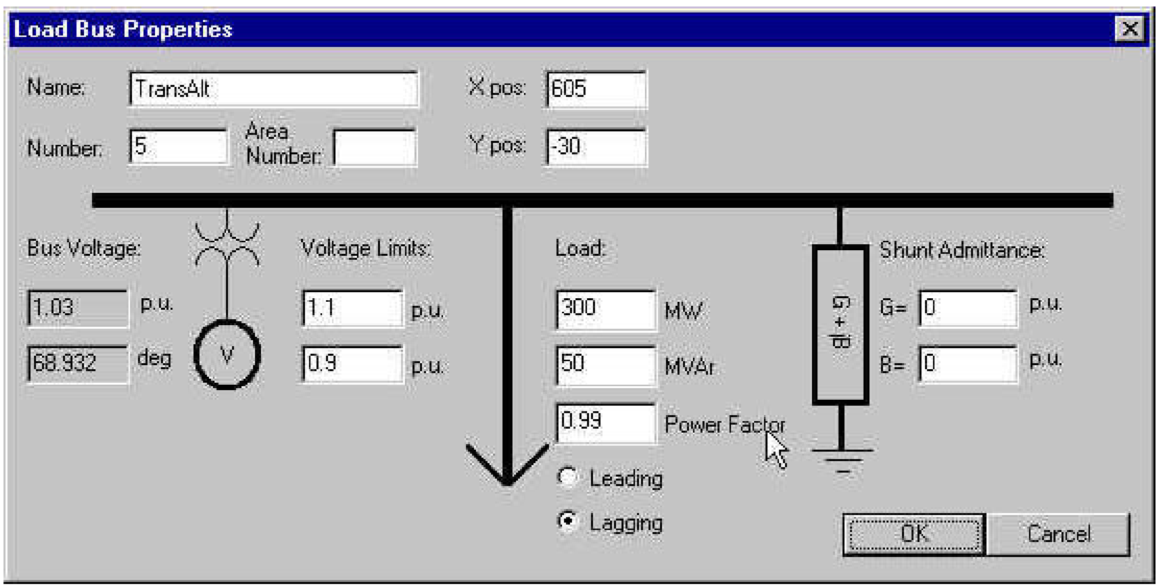


Figure 5.2 – Load bus data input dialog

The generator bus dialog is shown in figure 5.3. Its interface is similar to that of the load bus, other than the addition of the generator. Clicking on the generator button brings up a second dialog (not shown) which allows the user to input the machine characteristics needed for transient simulation.

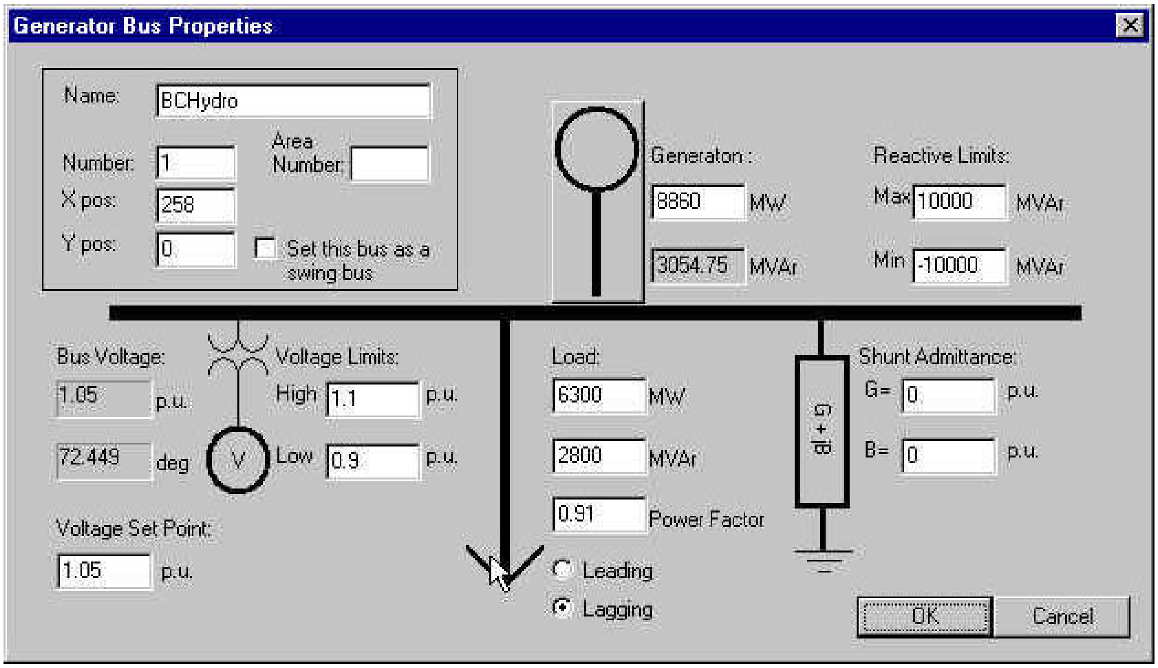


Figure 5.3 – Generator bus data input dialog

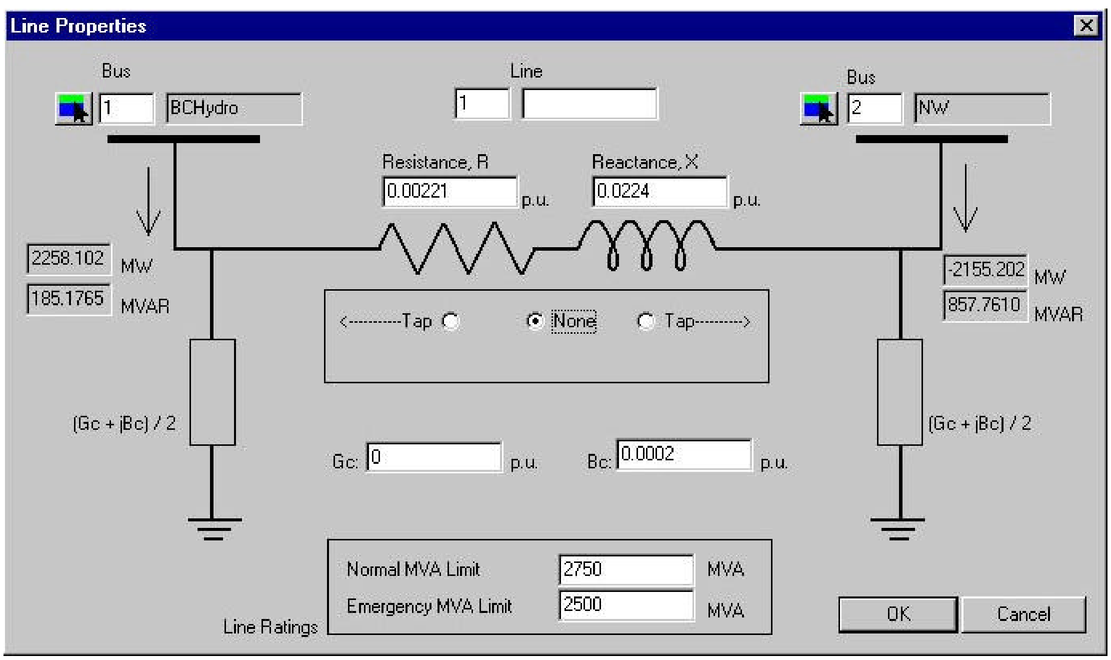


Figure 5.4 – Transmission line data input dialog

The transmission line data dialog box is shown in figure 5.4 Like the bus dialog boxes the data input boxes are overlaid on a one-line display of the transmission line. The resistance and reactance of the line are shown as a resistor and inductor in series. The shunt element is shown as a shunt impedance on each end of the line. The user can also add a transformer with an off-nominal tap on either side of the transmission line by indicating the location and the tap ratio. Selecting a tap location adds a small transformer schematic to the diagram indicating which side has the non unity turns ratio.

The intention of each of these dialog boxes is to enable students to more easily and intuitively enter and change the data required to simulate a power system. Since notation in power systems is not always consistent and since new power students may not have a good understanding of the data required to specify a power system, the graphics in these dialog boxes are intended to help students better understand the meaning of the required input data and thereby shorten the learning curve.

5.5.2 Contingency mode

As mentioned in section 5.4.4, the contingency mode in PowerViz was designed to enable students to view the effect of all the possible line outages as described in [Maha, 94]. The user can run the n-1 contingency calculation by choosing Tools | Contingency Analysis from the menu, or by changing to the contingency mode via the drop down box on the tool bar. The algorithm presently being used for the power flow is rather slow because it does not take advantage of the matrix sparsity inherent to power system matrices so the contingency calculation takes a noticeable amount of time to run. Currently the contingency calculation for a 30 bus, 42 line system takes 23 seconds on a Pentium II, 450 MHz PC. While the program is calculating a dialog box indicates the progress of the calculation. When the calculation is completed the view will change (see figure 5.5). The lines for which one or more contingencies cause an overload are colored in orange. Instead of showing the actual bus voltage on each bus, the most extreme bus voltage (high or low) is shown. In order to aid students in their analysis, the program makes it fairly easy to view the power flows which correspond to each line outage. Right clicking on one of the orange lines causes a drop-down menu to appear which lists all of the contingencies that cause an overload on this line. For example, in the system shown in figure 5.5, outages on lines 10, 11, and 20 cause overloads on line 7. The drop-down menu shown also indicates the magnitude of each overload (137%, 113%, and 101% in this case). The power flow corresponding to each of the listed outages can be viewed by choosing it from the menu.

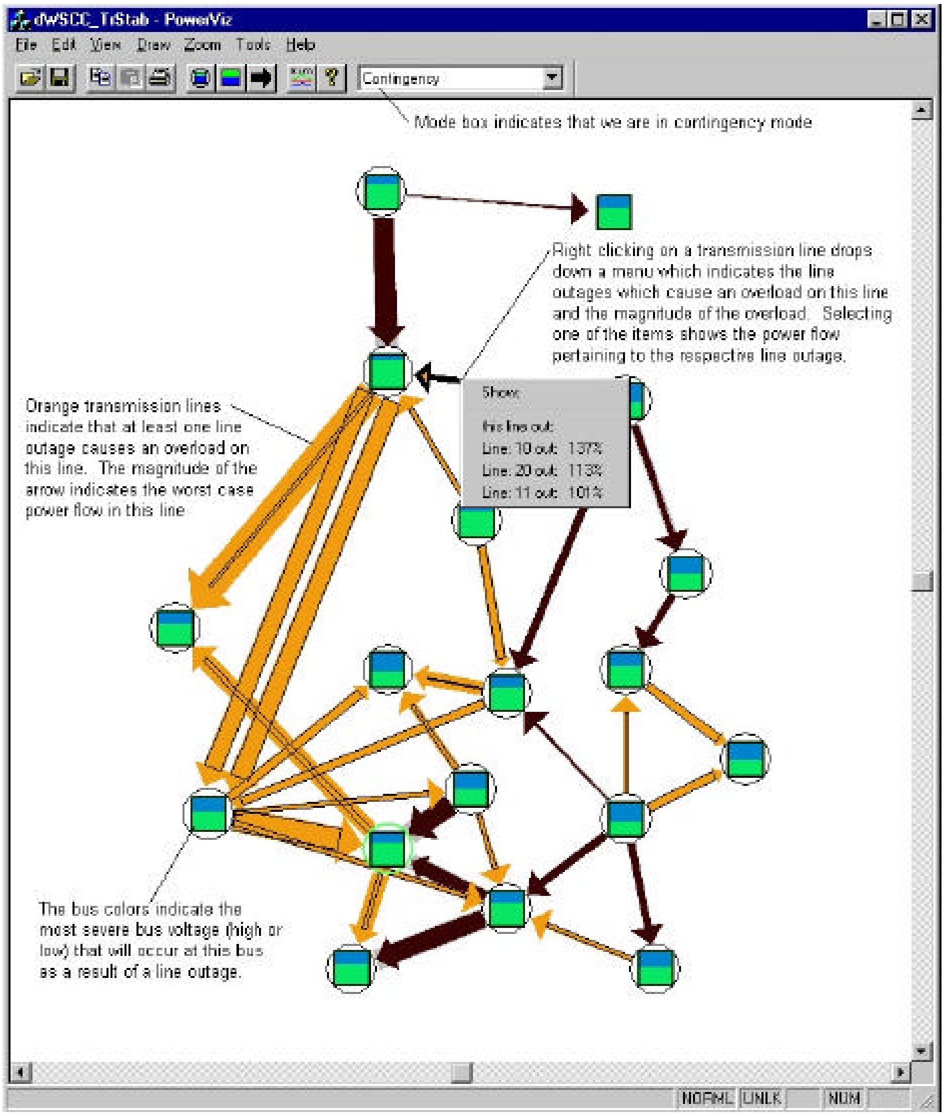


Figure 5.5 – Contingency mode user interface diagram. Line 7 has been right-clicked displaying the drop-down menu shown above.

5.5.3 Transient stability mode

The transient stability mode was designed to allow students to quickly analyze and assess the transient stability of a system. The user normally would access the transient stability mode by running a transient simulation. This can be done by selecting Tools | Transient Stability Analysis from the menu or clicking the sim button ( ) on the tool bar. This brings up a dialog (see figure 5.6) through which the user can input the sequence of events to be simulated. The program allows the user to simulate a variety of events including 3-phase faults, circuit breaker opening and reclosing, generator tripping, generator fast valving, and a shunt braking resistor. The fast valving and the braking resistor events were added to give students more design options when dealing with system stability problems. Some experimentation has shown that these features are rather difficult to use to reliably improve the system stability, as the value of the braking resistor (in per unit Ohms) and the fast valving (in per unit MW) must be specified carefully to obtain improved stability. The energy dissipated by the resistor or released through the valve must be calculated so that it is nearly equivalent to the additional energy in the system due to the fault. These features may be more useful in a graduate course on transient stability where students could be expected to carefully calculate the accelerating energy in the system due to the fault. Alternatively, these features could be rewritten so that the program calculates the fast valving and resistor per unit values as well as the active time-span automatically. This may more closely match the way that these technologies would operate in real power systems. The transient stability dialog box helps the user know what inputs are needed for different event types by activating only the input boxes which are needed for the selected event. The user can also specify which graphs he or she wishes to see and the calculation step size through this dialog box.

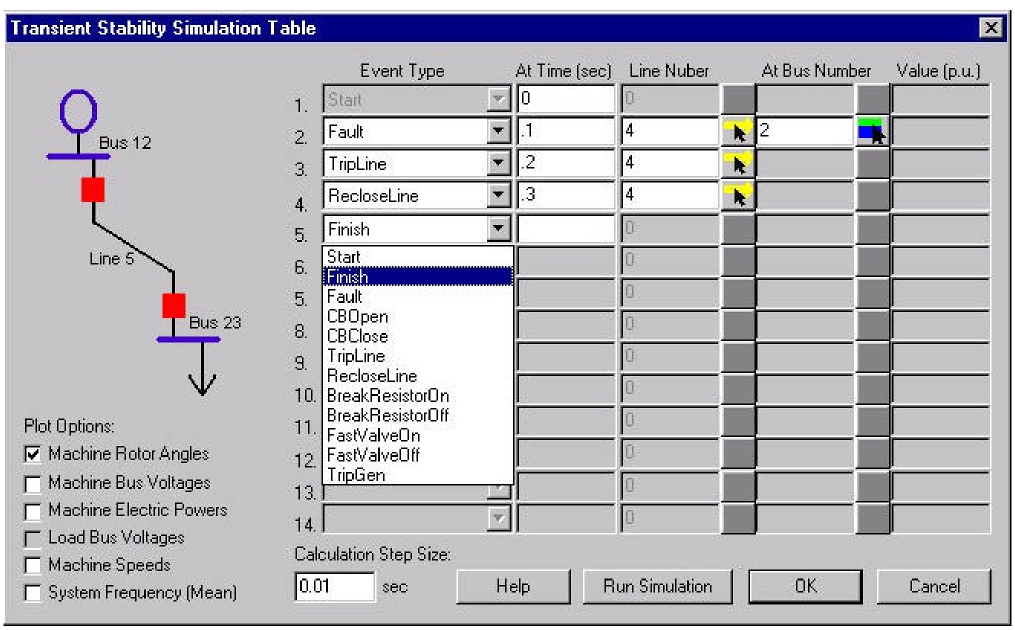


Figure 5.6 – Transient stability sequence of events input dialog

When the "Run Simulation" button is clicked the program calculates the state of each machine during every time step within the analysis time period. Because the calculation methods do not consider matrix sparsity, the calculation is rather slow for medium or large systems. A ten second simulation of the 17 machine WSCC system with a 0.01 second time step takes about 30 seconds on a Pentium II, 450 MHz PC. A dialog box indicates the progress of the calculation as it is in process.

When the calculation is complete, dialog boxes for each selected plot appear on the screen and the bus colors on the one-line display change to match the colors of the plotted curves (see figure 5.7). This use of color is intended to allow users to quickly associate the plotted curves with the associated generator buses. Our experience indicates that it is not difficult to quickly relate the machine angles on the time graph with the generator bus on the one-line display. This task seems easier than the same task using the non color coded display shown in figure 5.8. This hypothesis should be tested via experimentation to confirm our suspicions. While this color coding method seems to be useful for the purposes of this project, it has some drawbacks. Firstly, color-blind users will have trouble distinguishing between some of the colors, preventing them from correlating some of the curves with their corresponding buses. Future versions of the PowerViz program should combine a numerical legend with colored curves. Secondly, this display is only effective if the number of generators is fewer than the number of colors that the user can easily distinguish. Our experience with the colors showed that even with 17 buses it is a little difficult to distinguish between some of the colors. It may be possible to select colors that are more easily distinguished than those used in this display, increasing the number of machines that can be effectively visualized. The color coding method allows the user to recognize not only whether the system is stable or unstable, but also to see which generators swing together and which ones separate. Figure 5.9 shows an unstable case. In this case the power transfer between the northwest and California has been substantially increased. It can be quickly seen that the two northern generators disconnect from the rest of the system and then continue to swing together, creating an island. The student who has been given the task of mitigating this problem can use this information to see that some action should be done to bring these two generators electrically closer to the system. With this software the student has the ability to test the effect of circuit breaker reclosing, the addition of a transmission line, or a change in the scheduled generation with only a few UI manipulations.

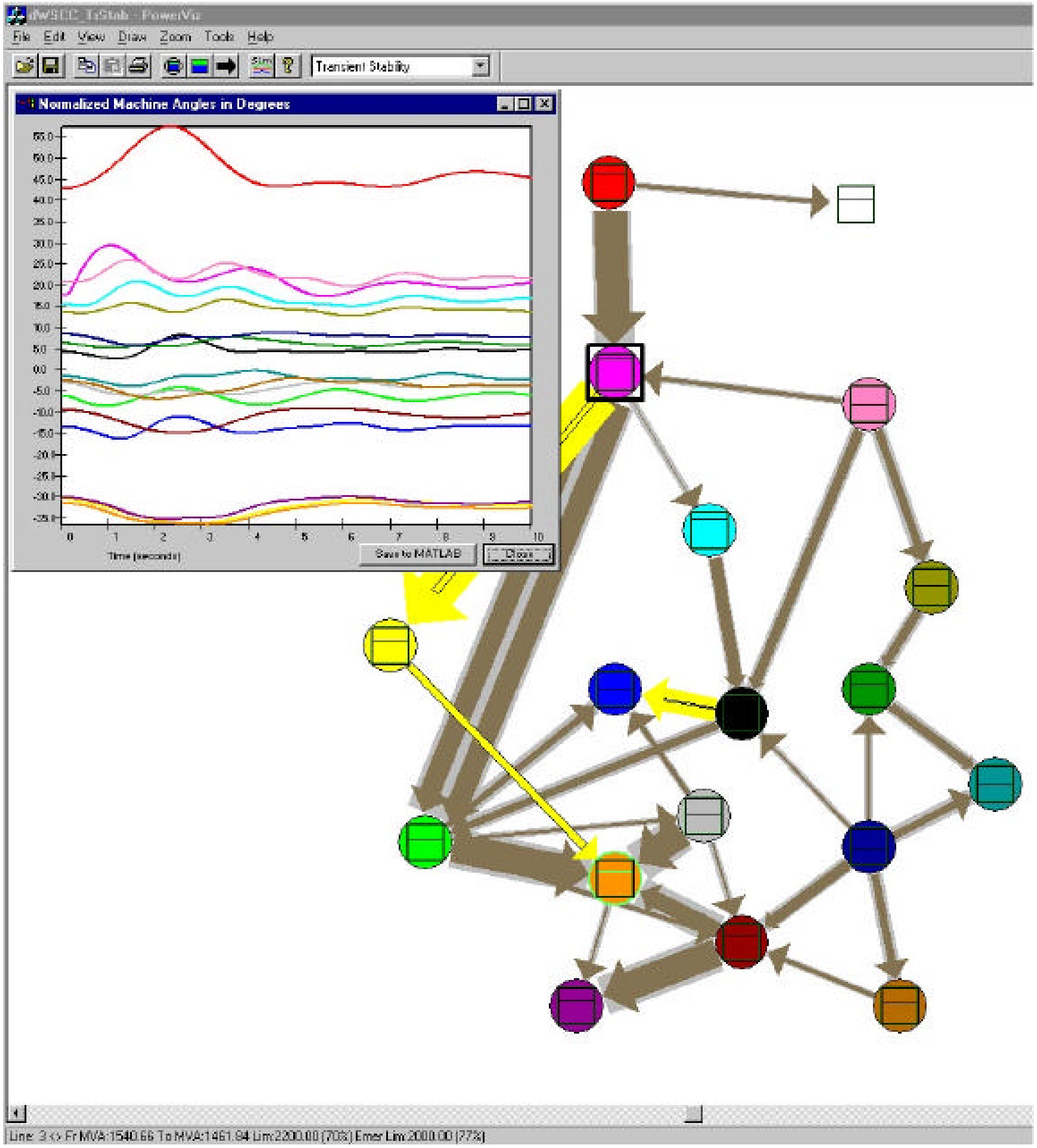


Figure 5.7 – WSCC system shown in transient stability mode with a stable machine angle plot

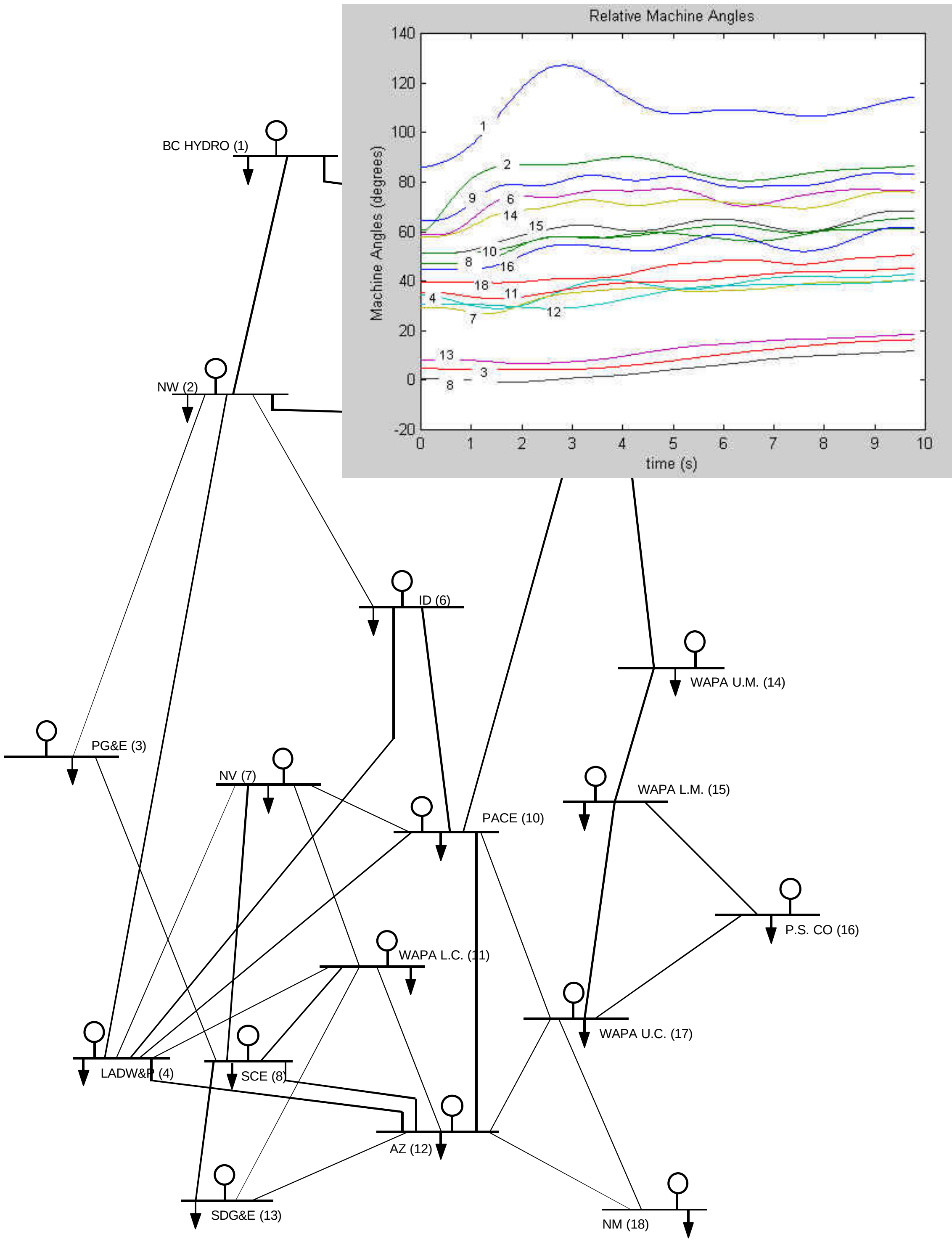


Figure 5.8 – Numerically coded one line and machine angles for the WSCC system

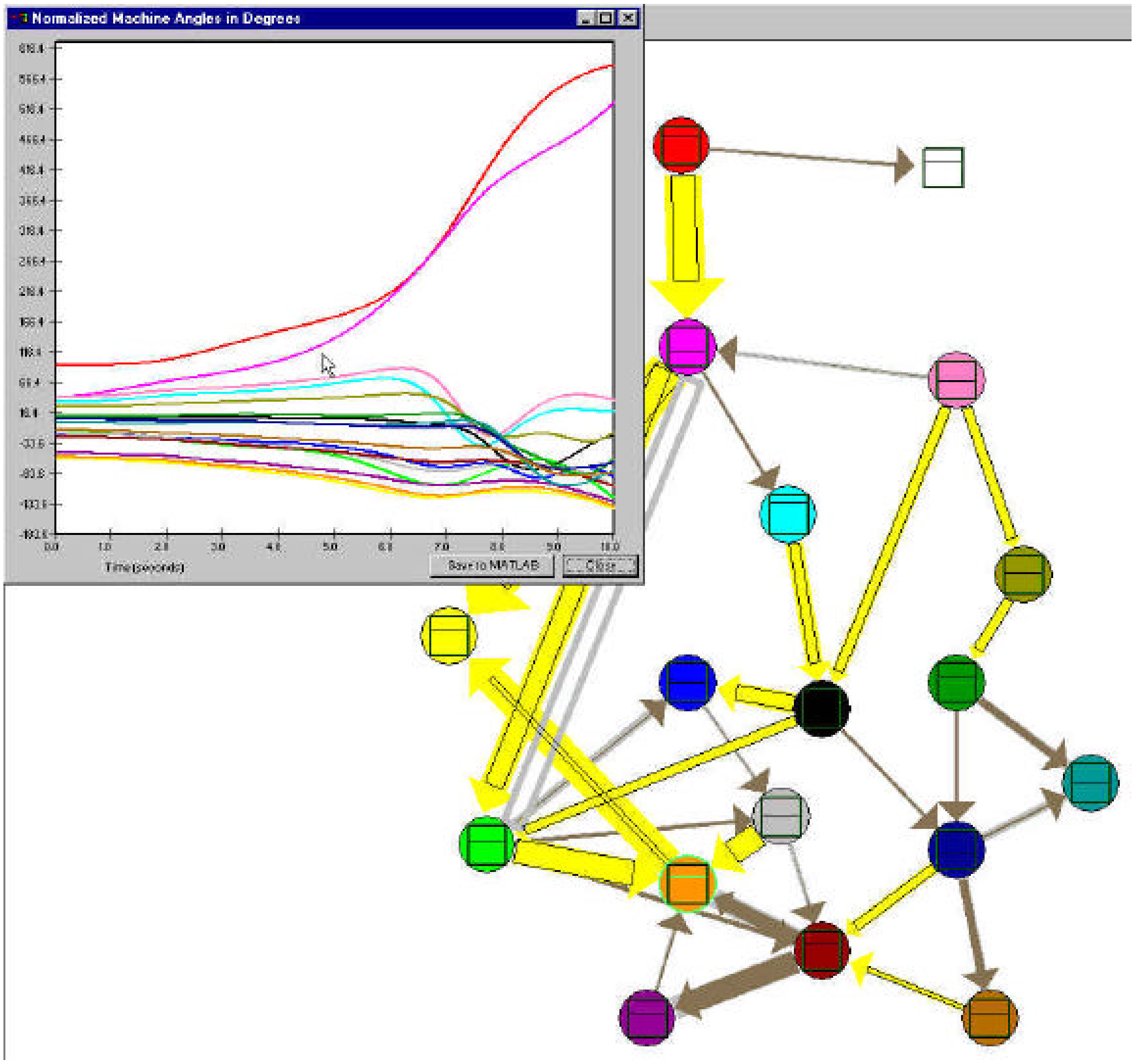


Figure 5.9 -- WSCC system shown in transient stability mode with an unstable machine angle plot

5.6 Numerical Solution of the n Machine Transient Stability Problem

Although power system engineers have been studying methods of evaluating the transient stability of a power system for decades, definitive determination of stability is a difficult problem that requires detailed models and careful calculation methods to do correctly. One cause of the August 10, 1996 disturbance on the WSCC system was that the model being used to simulate the system was inaccurate [Kost, 99]. There are many factors that go into accurately simulating the response of a power system to large transients. One must create models for all of the power system components, including loads, machines, transmission lines, and transformers. One must also choose event sequences to model which will accurately reflect the event sequences that are likely to occur in the real power system. Finally, one must choose a method for solving the algebraic and differential equations that result from the component models.

For the purposes of this program we use fairly simple component models because perfect calculation accuracy is not a goal of this project. Loads are modeled as complex impedances. A simplified two axis machine model without exciter or speed controller models is used for generators. Standard p models are used for transmission lines and transformers. The actual sequence of transient events must be selected by the user. In order to solve the differential equations PowerViz uses a fourth-order Runga-Kutta (RK4) differential algebraic solution method.

5.6.1 The differential algebraic solution method

In its most generic form, the solution of a multi-machine time-domain transient problem is done by solving for the steady state characteristics of a system and then repeatedly solving a set of differential and algebraic equations to determine the state of the system in during the next time step (t+? t). The differential equations in their simplest form can be written as:

$$\dot{x} = f(x, \bar{I}, u) \tag{5.1}$$

and the algebraic or network equations as:

$$\bar{I} = g(x) \tag{5.2}$$

where x is a vector of the machine state variables, $\bar{I}$ is a vector of the internal machine currents, and u is a vector of the machine inputs. f is the set of machine differential equations from our machine model and g is a system of equations which represent the power system network equations. The machine internal voltages are calculated during each time step, but are not essential for solving the above generalized equations.

5.6.2 The 4th order Runga-Kutta time domain solution algorithm

In this program a fourth order Runga-Kutta (RK4) algorithm was used to solve the differential equations above. The RK4 algorithm was used for this program because of its computational efficiency and accuracy. It is substantially more accurate and efficient than Euler or trapezoidal methods [Onei, 95]. Many time domain simulation algorithms use predictor-corrector methods as these are somewhat more reliable at solving stiff differential equations [Stag, 68]. A predictor-corrector method was not used because these methods are substantially more difficult to code than the implemented RK4 algorithm. The RK4 method consists of the calculation of four weights (W_{k1}, W_{k2}, W_{k3}, and W_{k4}), and then using these weights to calculate the machine state at the next time step. Equations 5.3-5.7 are the general form for the solution of a differential equation: $dy/dx = f(x,y)$.

$$W_{k1} = f_k \tag{5.3}$$

$$W_{k2} = f\left(x_k + \frac{h}{2}, y_k + \frac{hW_{k1}}{2} \right) \tag{5.4}$$

$$W_{k3} = f\left(x_k + \frac{h}{2}, y_k + \frac{hW_{k2}}{2} \right) \tag{5.5}$$

$$W_{k4} = f\left(x_k + h, y_k + hW_{k3} + hW_{k3}\right) \tag{5.6}$$

$$y_{k+1} = y_k + \frac{1}{6} h\left(W_{k1} + 2W_{k2} + 2W_{k3} + W_{k4}\right) \tag{5.7}$$

Combining the RK4 algorithm above and the differential algebraic method, the following steps are used to solve for the electrical and mechanical machine states during the solution time period:

1. Solve the steady state power flow.
2. Calculate the initial conditions (x, $\overline{V}$, and u) of the system.
3. Form the reduced admittance matrix ($\hat{Y}_{red}$) from the existing admittance matrix and the system loads using:

$$\hat{Y}_{red} = Y_{gg} - Y_{gl} \cdot Y_{ll}^{-1} \cdot Y_{\mathrm{lg}} \tag{5.8}$$

where Y_{gg}, is a matrix of the $\hat{Y}_{bus}$ components corresponding to the generator buses, Y_{ll} is a matrix of the $\hat{Y}_{bus}$ components corresponding to the load buses, and Y_{lg} and Y_{gl} are matrices of the $\hat{Y}_{bus}$

components corresponding to the interconnections between the load and generator buses. $\hat{Y}_{bus}$ is the bus admittance matrix including the impedance equivalent loads; thus:

$$\hat{Y}_{bus} = Y_{bus} + Y_{load} \tag{5.9}$$

where Y_{load} is a diagonal matrix of the admittance equivalents of the loads at all the buses in the system and Y_{bus} is the power flow admittance matrix.

4. Calculate W_{k1}:

$$W_{k1} = f\left(x_k, I_k, u_k\right) \tag{5.10}$$

where f is a vector of the differential equations as given in 5.15-5.18.

5. Calculate W_{k2}:

$$W_{k2} = f\left(x_k + \frac{W_{k1}}{2}dt, g\left(x_k + \frac{W_{k1}}{2}dt\right), u_k\right) \tag{5.11}$$

6. Calculate W_{k3}:

$$W_{k3} = f\left(x_k + \frac{W_{k2}}{2}dt, g\left(x_k + \frac{W_{k2}}{2}dt\right), u_k\right) \tag{5.12}$$

7. Calculate W_{k4}:

$$W_{k4} = f\left(x_k + W_{k3}dt, g\left(x_k + W_{k3}dt\right), u_k\right) \tag{5.13}$$

8. Calculate x_{k+1}:

$$x_{k+1} = x_k + \frac{1}{6}\left(W_{k1} + 2W_{k2} + 2W_{k3} + W_{k4}\right)dt \tag{5.14}$$

Finally the program advances k and t (the simulation time) and repeat steps 3-8 until the end of the simulation is reached.

5.6.3 The simplified two-axis machine model

As mentioned earlier, a simplified two-axis machine model is used to simulate generators in the system. This model neglects the effects of the sub-transient machine reactances and time-constants, as well as hysteresis in the machine windings. The model is taken from equations 7.1-7.4 of Sauer and Pai [Saue, 98]. The equations are given below with only minor modifications. All variables are in per-unit with respect to the system MVA base unless otherwise noted.

$$T_{d0}'\frac{dE_q'}{dt} = -E_q' - (X_d - X_d')I_d + E_{fd} \tag{5.15}$$

where E_q' is quadrature axis internal machine voltage, T_{d0}' is the direct axis transient time constant (in seconds), X_d is the direct axis synchronous machine reactance, X_d' is the direct axis transient machine reactance, I_d is the direct axis machine current, and E_{fd} is the winding field voltage.

$$T_{q0}'\frac{dE_d'}{dt} = -E_d' + (X_q - X_q')I_q \tag{5.16}$$

where E_d' is direct axis internal machine voltage, T_{q0}' is the quadrature axis transient time constant (in seconds), X_q is the quadrature axis synchronous machine reactance, X_q' is the quadrature axis transient machine reactance, and I_q is the quadrature axis machine current.

$$\frac{dd}{dt} = w - w_s \tag{5.17}$$

where *d* is the machine angle (in radians), *?* is the machine's angular speed (in radians/second), and $?_s$ is the system synchronous angular speed ($?_s = 2\ p\ f_s$ where f_s is the system frequency).

$$\frac{2H}{w_s}\frac{dw}{dt} = T_M - E_d'I_d - E_q'I_q - (X_q' - X_d')I_dI_q - D(w/w_s - 1) \tag{5.18}$$

where *H* is the machine's rated inertia, T_M is the mechanical torque on the shaft of the machine, and *D* is the machines rated damping coefficient. Equation 5.18 is slightly modified from that presented in Sauer and Pai's text. Sauer and Pai show the damping torque term in equation 5.18 as $D(w - w_s)$. The discrepancy may be due to a factor of $?_s$ difference in the definition of the damping coefficient *D*.

5.6.4 The network solution method

The network solution method for this problem consists primarily of solving for the bus voltages and injection currents of the reduced system along the direct and quadrature machine axes. This method is based on the basic network equation of the system:

$$\bar{I} = \hat{Y}_{red}\bar{V} \tag{5.19}$$

where $\bar{I}$ and $\bar{V}$ are vectors of the complex bus voltages and bus injection currents at the machine buses only. Secondly we use the definitions of the direct and quadrature axis current and voltages (as defined by Sauer and Pai):

$$\bar{V} = g\,(V_d + jV_q) \tag{5.20}$$

where V_d and V_q are vectors of the direct and quadrature axis machine voltages and *?* is a diagonal matrix angel shift matrix such that:

$$g_{i,i} = e^{j\left(d - \frac{p}{2}\right)} \tag{5.21}$$

Similarly the direct and quadrature axis current relationships are defined by:

$$\bar{I} = g\,(I_d + jI_q) \quad \text{i=1…m} \tag{5.22}$$

where *m* is the number of machines. Using the simplified machine model of Sauer and Pai, each machine is modeled as a dependent voltage source behind the machine's series resistance (R_s) and transient reactance (jX_d'). Using this model Sauer and Pai define the following relationship between machine voltages and machine currents:

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} R_s & -X_q' \\ X_d' & R_s \end{bmatrix}^{-1} \begin{bmatrix} E_d' - V_d \\ E_q' - V_q \end{bmatrix} \tag{5.23}$$

thus:

$$I_d = A(E_d' - V_d) + B(E_q' - V_q) \tag{5.24}$$

$$I_q = C(E_d' - V_d) + D(E_q' - V_q) \tag{5.25}$$

where we define *A*, *B*, *C*, and *D* as diagonal matrices with the diagonal elements defined as follows:

$$A_{i,i} = \frac{R_s}{R_s^2 + X_d' X_q'} \quad \text{i =1…m} \tag{5.26}$$

$$B_{i,i} = \frac{X_q'}{R_s^2 + X_d' X_q'} \quad \text{i =1…m} \tag{5.27}$$

$$C_{i,i} = \frac{-X_d'}{R_s^2 + X_d' X_q'} \quad \text{i =1…m} \tag{5.28}$$

$$D_{i,i} = \frac{R_s}{R_s^2 + X_d' X_q'} \quad \text{i =1…m} \tag{5.29}$$

Using equations 5.26 – 5.29 above we can solve for the machine currents and voltages given the electro-mechanical state of the machine (E_d', E_q', and *d*). Firstly, we substitute 5.21 and 5.23 into 5.20 to get:

$$g\left(I_d + jI_q\right) = \hat{Y}_{red} g\left(V_d + jV_q\right) \tag{5.30}$$

thus:

$$\left(I_d + jI_q\right) = g^{-1}\hat{Y}_{red} g\left(V_d + jV_q\right) \tag{5.31}$$

In order to separate 5.32 into its real and reactive parts we define two matrices *G'* and *B'* so that:

$$G' = \mathrm{Re}\left[g^{-1}\hat{Y}_{red} g\right] \tag{5.32}$$

$$B' = \mathrm{Im}\left[g^{-1}\hat{Y}_{red} g\right] \tag{5.33}$$

thus:

$$I_d = G'V_d - B'V_q \tag{5.34}$$

and

$$I_q = B'V_d + G'V_q \tag{5.35}$$

Combining equations 5.25 and 5.35 gives:

$$G' \cdot V_d - B' \cdot V_q = A\left(E_d' - V_d\right) + B\left(E_q' - V_q\right) \tag{5.36}$$

Similarly, combining 5.26 and 5.36 gives:

$$B' \cdot V_d + G' \cdot V_q = C\left(E_d' - V_d\right) + D\left(E_q' - V_q\right) \tag{5.37}$$

Combining 5.36 and 5.37 into a single matrix equation results in:

$$\begin{bmatrix} G'+A & -B'+B \\ B'+C & G'+D \end{bmatrix} \begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} AE_d'+BE_q' \\ CE_d'+DE_q' \end{bmatrix} \tag{5.38}$$

Using 5.38, we can solve for V_d and V_q using matrix methods. Once V_d and V_q are known, I_d and I_q can be calculated using 5.27 and 5.28.

5.7 Summary

In this chapter we have discussed a power system simulation tool for use in engineering education. While none of the algorithms are as effective as those used in professional simulation tools, it is believed that the user interface methods used will be useful in an educational setting. A new method of using color codes to identify machine curves was developed and implemented. While this method is not vastly superior to the traditional method of displaying time-domain machine curves with alpha-numerical labels, this method may help students working on small to medium sized transient stability problems quickly relate the time-domain graphs to the actual power system. Presently, this software is being used in a power systems analysis course with a transient stability design problem at the University of Washington. Because the PowerViz software is significantly easier to use than the program used in previous offerings of the course, the design problem given to the students is significantly more difficult and comprehensive than the problem given to students in pervious years. In sum, this is the goal of the PowerViz software: to free students from needing to spend time and energy thinking about power systems software, allowing students to spend more time and energy thinking about power systems. The hope is that in the long-run this will lead to power systems graduates who are better prepared to contribute to the electrical power industry.

6 An Experiment Using the PowerViz Software

In order to compare the PowerViz software with an alternative that does not make extensive use of visualization, an experiment was developed and partially implemented. The experiment was intended to test whether students using the software can perform a simple iterative design task with greater speed and understanding with PowerViz than with a MATLAB command line program known as the Power System Toolbox (PST). In the design problem students were asked to simulate a fault on a 3 machine system, and then adjust the power in the three generators until a stable operating condition was found where none of the transmission line-flows were above the specified line limits (see figure 6.1). Eight students completed the test (5 with PowerViz and 3 with the PST). After analyzing the preliminary data obtained from these 8 students, it was realized that there is not a significant difference between the two programs using this design problem. After further contemplation, this result seems reasonable since the three-machine iterative problem used in this case can be easily solved via a simple “guess and check” process. Very little conceptual understanding of the power system’s operation was required. The only feedback that the student needed from the analysis software was binary: is the dispatch stable, and does this dispatch cause any line overloads. Both PowerViz and the PST tools are equally effective at presenting binary results.

6.1 Test Hypotheses

The following are the four hypotheses which we sought out to test through this experiment:

> The use of graphically oriented transient stability software (such as PowerViz) should help students to:
>
> 1. complete a simple design task in less total time when compared with students using a MATLAB command line simulation package.
> 2. complete a simple design task with fewer total simulation iterations when compared with students using a MATLAB command line simulation package.
> 3. complete individual simulation iterations in less time when compared with students using a MATLAB command line simulation package.

4. achieve a greater qualitative understanding of the engineering science behind a simple design task when compared with students using a MATLAB command line simulation package.

6.2 Test Procedure

Student volunteers were solicited for this test via e-mail and class announcements. The student participants were primarily undergraduate students who had taken an introductory course in power systems, but had not studied transient stability. Because of this, when the student (or students) came in to complete the test the student was given a short lesson in transient stability. In this short lesson it was explained why the generator output power approaches zero during a bus fault and why the machine accelerates during the fault. The machine dynamics were initially explained by making a comparison between a power system and a system of interconnected water pipes with pumps (generators) and sprinklers (loads). Once the students seemed to have a basic understanding of transient stability the following procedure was followed to complete the test:

1. Use MATLAB to generate a random number. If the number is greater than .500 load the *Power System Toolbox,* otherwise load *PowerViz.*

2. Give a 10 minute demonstration of how to use the simulation tool.

3. Give the student a 5 minute explanation of the problem. The students were first asked to read through the problem individually and then it was explained orally.

4. Have the student start the design task. While students performed the test the computer recorded the time for each transient stability simulation iteration.

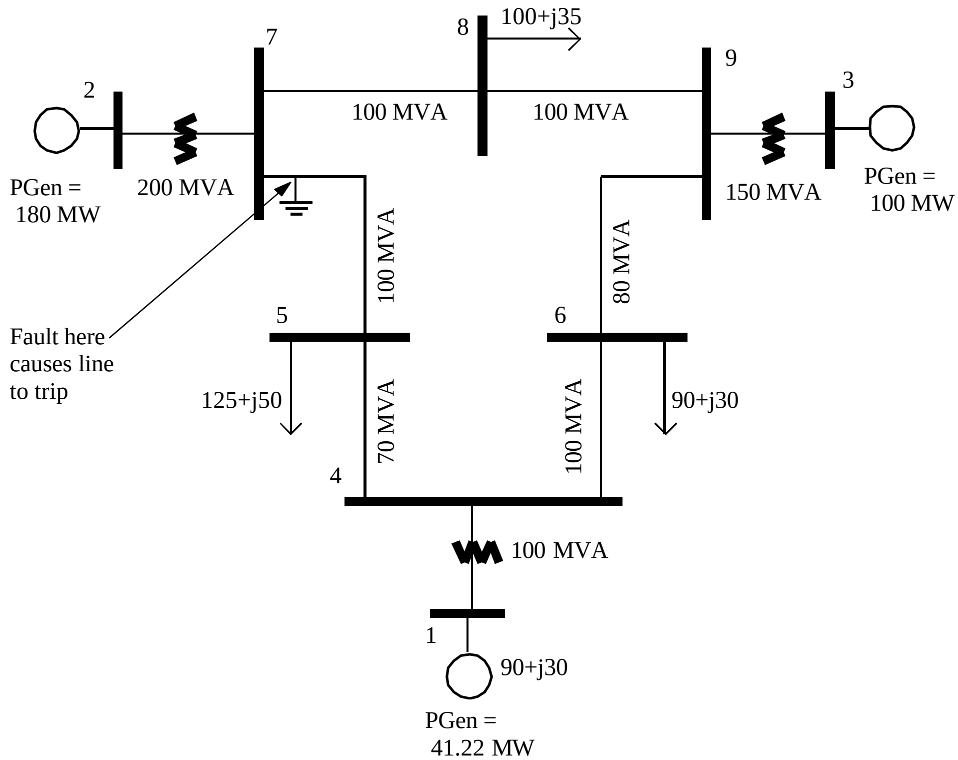
6. While the student is completing the design problem, take general notes about the student's method.

7. Once the student has completed the design task, ask the student some conceptual questions about their understanding of the probe and record his or her remarks.

8. If the student is using *PowerViz,* ask the student for his or her general reactions to the program.

Transient Stability Design Problem

The utility that operates the system depicted below has found that a fault near bus 7 on the line between buses 7 and 5 may cause the system to become unstable. This fault occurs relatively frequently and is thought to be the worse case fault on this system. They have asked you to help them to determine a stable operating point for their three generators (given this fault). The maximum operating limits for all lines and transformers must be observed. Find a stable operating point that does not violate any of the line or transformer limits for the nine-bus system by increasing or decreasing the generator (MW) outputs. The MVA ratings shown on the transmission lines and transformers below indicate the normal operating limit for these components.



The utility does not want to operate in this insecure state any longer than is absolutely necessary, so they expect you to find the new operating condition in as little time as possible.

Figure 6.1 – Text of the experiment problem as given to students

6.3 Results

At first glance our tests seemed to indicate that there was a significant difference between the total time required by students using PowerViz and students using the PST. The average total completion time for student using PowerViz was 4 minutes and 20 seconds, whereas the total time for students using the PST was 6 minutes and 56 seconds. In order to calculate whether this difference was statistically significant we state the null hypothesis as:

$$H_0: \mu_1 - \mu_2 = 0 \tag{6.1}$$

where μ_1 is the mean PowerViz completion time and μ_0 is the mean PST completion time. Using a confidence level a=0.05, we calculated that the t score would need to be a member of the range:

$$t < -2.447 \text{ or } t > 2.447 \tag{6.2}$$

in order to reject the null hypothesis. The t score for the completion-time test came out to t = -0.883, thus we cannot confidently reject the null hypothesis.

It must also be noted that the PST transient stability tool is significantly slower than the PowerViz tool for three machine calculations. The PST requires about 20 seconds to complete a three second simulation of the three machine system on a Pentium II, 450MHz PC. The same calculation can be completed almost instantaneously using the PowerViz program. If we remove 20 seconds per iteration from the total time of each of the three students who used PST to complete the design problem, the difference between the PST and PowerViz completion times is reduced to about 2 seconds (4:20 for PowerViz, 4:22 for PST). With this small a deviation we certainly cannot reject the null hypothesis. Therefore we must concluded that for the design problem in question, the use of PowerViz has little or no effect on the total completion time. Unfortunately the student answers to questions about conceptual understanding of the 9 bus system were not informative enough to make any real connections between student understanding and the use of visualization.

It is possible that if we had continued this test and gathered more subjects under more carefully controlled circumstances, we would have come to slightly different conclusions, but I feel that the test, as it was originally designed, was not going to lead us to learn anything useful. The software was not being tested under the circumstances that it was designed for. I feel that the design problem described above is too simplistic to see the effect of visualization on design behavior. Nevertheless, the effect of visualization on design behavior is an interesting area of research with many open questions which are as of yet un-explored.

7 Conclusions

In this thesis a new design project that combines transient stability, market economics, and political issues has been developed. In order to aid students in the power systems analysis of this problem and problems like it a visual power systems analysis software package has been developed. The design project was used in a capstone power systems design course with reasonable success. The software is presently being used as the simulation tool for a transient stability project in an intermediate power systems analysis course. Because of the program's relatively simple user interface, students are being asked to complete a more difficult design problem than the problem used in previous offerings. Both the design project and the analysis tools have the common purpose of improving power systems education. Hopefully the design project will encourage students to think at a higher level (on Bloom's taxonomy scale for example) about power systems. Similarly the intention of PowerViz is to encourage students to think on a higher level about power systems. Our thinking is that the use of visualization and minimal user interactions will help students to move away from thinking about the analysis software and to expend greater effort thinking on a high level about the power system. Hopefully students will carry this higher level of thinking with them into industry, leading them to be better able to contribute to the rapidly changing power systems industry.

7.1 Future Work

Several important and interesting questions came up during the course of this project. The first relates to the use of color to relate transient stability machine curves with system buses as discussed in section 5.5.3. Does this method of visualization lead to faster user interaction? It seems logical that it would as research has indicated that graphical displays generally lead to faster comprehension. Secondly, does this method of visualization lead to better understanding in general? This is a more difficult question that is not as easily answered.

The experiment that we describe in chapter 6 was a first attempt at exploring the relationship between visualization and iterative design behavior. Originally, I was quite convinced that visualization would lead to “better” design behavior. I am not sure that this is necessarily so now. Does the use of WYSIWYG word processing tools result in better written text? In power systems this is an important question forfor power system operators who are considering upgrading their operations control centers. How much benefit is there to graphics in a design situation?

The work that we have begun is only of limited value if it remains at the University of Washington. The design project and analysis tools developed in this project are part of a larger program through which the NSF is seeking to get innovative instructors to design good undergraduate curriculum and then to share this curriculum with other universities for use in their engineering programs. We plan to post our software and curriculum to a web site, and inform others that the software is available.

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Appendix I – Transient Stability Problem Statement

The following pages are a reprint of the original problem statement as given to students in EE 456 “Computer-Aided Design in Power Systems,” at the University of Washington, during Spring quarter of 2000.

Memo

To: All parties concerned with WSSOC transmission system planning.

From: WSSOC transmission planning committee

Re: WSSOC System Status and Request for Proposals

The past five years have brought major changes in the western region electrical system. With competitive markets active throughout the region, and with increasing regional demand growth, the electrical transmission grid must adapt to meet increased demand, maintain economic efficiency, and sustain reliability margins. With locational marginal prices volatile and varied across control areas there is a steady demand for an increase in the available transfer capacity (ATC) between control areas. In particular the ATC between the Northwest and California is substantially limited by the transient stability margin. Over the next eight years, as load grows and transfer increases, there will be a continuing need to improve the transmission system.

Presently the WSSOC is maintaining ATC across the California-Oregon Intertie (COB) at the 1998 levels which were established after extensive investigation into the July and August 1996 system disturbances. The attached one-line and data represent normal summer peak operating conditions at the established 1998 levels. Since its inception three months ago, the WSSOC transmission planning committee has begun to consider transmission system improvements for the western region network. In order to consider the views of as many interested parties as possible, the WSSOC will be hearing recommendations from interested organizations before action is recommended to member ISO planning groups.

Presentations by any interested parties will be heard on ____________ and must be accompanied with a report detailing the actions recommended to the committee and the technical and economic rationale for the proposed actions.

The following guidelines should be adhered to when preparing reports and presentations for this meeting:

a. Reports should give a description of the security and transient stability analysis conducted on the included base case system data. This section should include an estimation of the transient stability margin from the present operating levels (given in the enclosed data file—*dWSCC2.m*). North to South ATC should be calculated by increasing the Northwest generation and the California loads until the system is not transient stable. The difference between the original generation schedule and the instable generation schedule is the ATC.

b. Reports should recommend a North to South ATC plan on the COB for each year in the given planning period.

c. Reports should detail all transmission upgrades recommended. The economic impact of all recommendations should be outlined. The economic data given in Table 1 should be used in any economic analysis of alternatives. System upgrades can be in terms of transmission system controls updates, or transmission line construction. Encouraging new generation capacity in certain areas in addition to the predicted generation growth can be recommended if it is found to be economically justifiable and feasible.

Interest Rate	5%
Planning Period	1 Jan. 2001 – 1 Jan. 2009
Load Growth	See reference [1] and attached spreadsheet
Generation Growth	See reference [1] and incremental cost approximations
Transmission Line Construction:*	
230kV 1000A	$ 325,000 / mi
230kV 2000A	$ 350,000 / mi
230kV 3000A	$ 450,000 / mi
500kV 2000A	$ 700,000 / mi
500kV 3000A	$ 900,000 / mi*
Double Circuit version of one of the above	Price*1.5
High Speed (3 cycle) Relaying and Circuit Breakers	$ 20,000,000 per equivalent bus/area
Additional Generation	$ 450,000 / MW

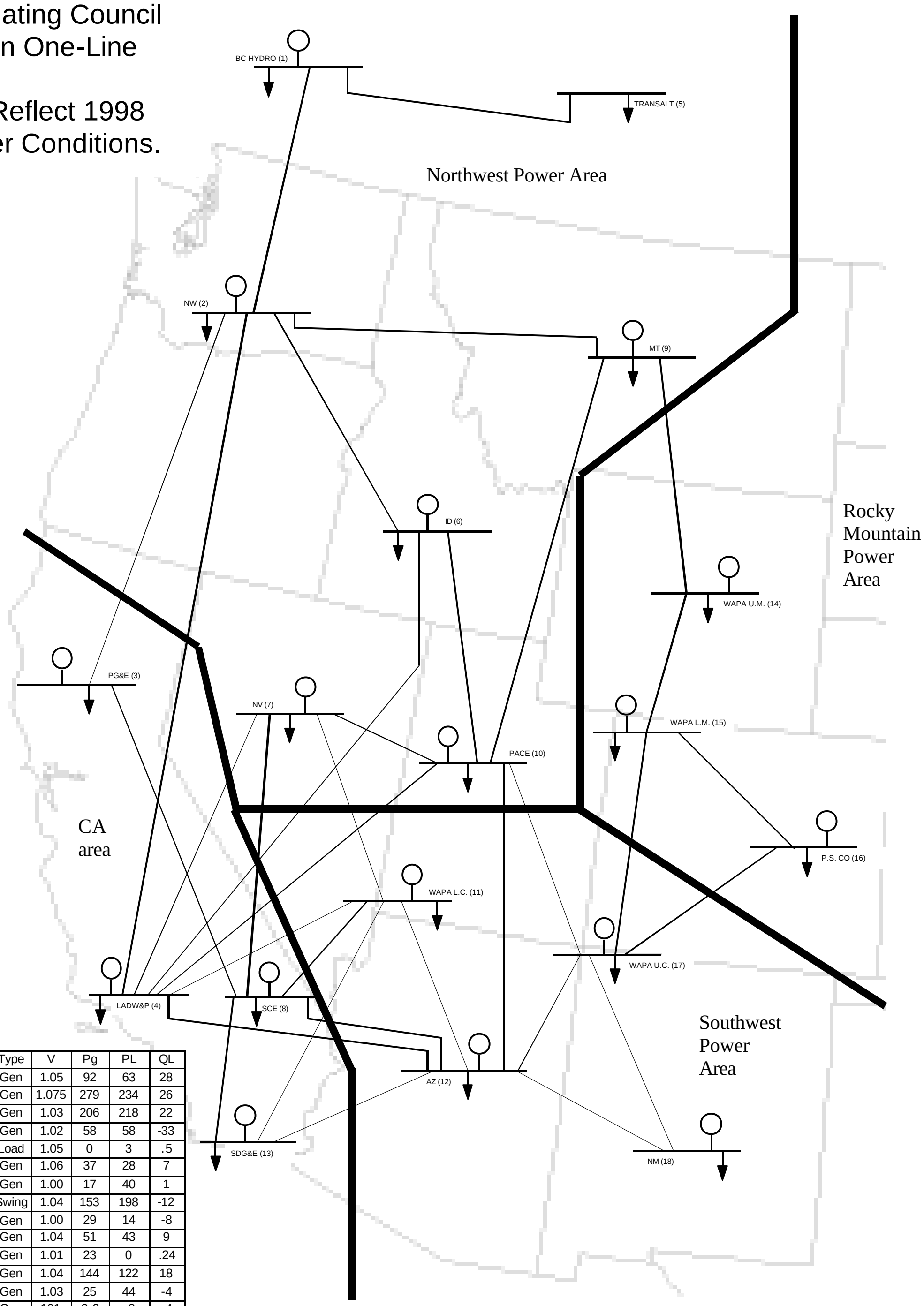
d. Each presenting group will be given 25 minutes to present their proposal to the planning committee. Five minutes of this time should be set aside for committee questions.

In October 1999 the WSCC gave a full report on the western region in terms of load growth predictions and reliability margins.[1] This data will be used by the planning committee in its recommendation to member Regional Transmission Operators (RTOs), therefore this data should also be used in reports to the planning committee.

[1] WSSOC, "10 Year Coordinated Plan Summary." http://www.wscc.com/10yrpt99.pdf
* Transmission Line Cost estimates by Erik Hale and Otto Lynch, Black & Veatch Corp. Transmission lines of other capacities can be estimated by interpolating the listed values.

Simplified Western System Coordinating Council Region One-Line

Data Reflect 1998 Summer Conditions.



Bus Data:

#	Name	Type	V	Pg	PL	QL
1	BCHYDRO	Gen	1.05	92	63	28
2	North West	Gen	1.075	279	234	26
3	PG&E	Gen	1.03	206	218	22
4	LADW&P	Gen	1.02	58	58	-33
5	Trans Alt	Load	1.05	0	3	.5
6	Idaho	Gen	1.06	37	28	7
7	Nevada	Gen	1.00	17	40	1
8	S. Cal. Edison	Swing	1.04	153	198	-12
9	Montana	Gen	1.00	29	14	-8
10	PACE (Utah)	Gen	1.04	51	43	9
11	WAPA L.C.	Gen	1.01	23	0	.24
12	Arizona	Gen	1.04	144	122	18
13	SD G&E	Gen	1.03	25	44	-4
14	WAPA U.M (WY)	Gen	101	2.2	.8	.4
15	WAPA L.M.	Gen	1.03	27	27.5	6
16	PS Colorado	Gen	1.00	37	47	7
17	WAPA U.C.	Gen	0.99	28	6	4
18	New Mexico	Gen	1.02	31	32	4

100 MVA Base

Hines, 10 Feb. 2000

Scale: 1” = 178mi

Transient Stability Design Problem

Attached is a report by the (fictional) WSSOC regarding its request for recommendations regarding its transmission system plan for the next 8 years. Your design group has been hired by one of the below organizations to help to prepare and present a report on their viewpoint to the WSSOC on _________ .

Your task is to complete the project as outlined in the attached report and present your results to the committee (i.e. the class and professor) via a report and an oral presentation.

The following are descriptions of the groups who are seeking engineering representation at the meeting:

Northwest Gen. Co. – You have just installed a state-of-the art 50 MW generator in the Northwest. Although, you will be able to sell your power in the Northwest market, you know that you can get a higher price for your electricity if you can sell across the Northwest/California intertie (COB). You and a group of engineers from similarly concerned generation-owners hope to propose design changes which will show that transfer limits can be increased to meet the increased load growth. You must show that the capital investment required by your design is justified.

Citizens for Reliable Electricity – This is a group of concerned citizens who feel that high transfer limits are a danger to system reliability. They cite the two major western system disturbances of 1996. Included in this group are former utility-engineers who feel that each area should be able to provide generation to meet the local load, and that energy markets have become over-dependent on “dangerous” inter-area energy transfer. Also included in this group are some Northwest environmentalists and fisherman who feel that the burden on Northwest hydro-electric plants has already over taxed the fish population. They advocate that transfer limits on the intertie should be reduced, not increased, and a very high margin of reliability should be maintained.

Pacific Northwest ISO -- The newly created Northwest ISO is watching the transfer limit question very carefully. The new company is nominally objective but is heavily composed of Northwest utility company employees (i.e. BPA, PSE, local PUD's, etc) and have close ties to Northwest public utilities commissions and congressional delegations. The NWISO is therefore primarily concerned about what will most benefit the Northwest energy economy. The NWISO also has a desire to maintain a high stability margin. There are concerns that another major outage similar to the ones which occurred in 1996 could bring major lawsuits to the NWISO.

University of Washington Economists – Economists at UW have been watching the changes in the western region energy market carefully. The changing market has posed numerous interesting questions about market structure, as well as topics for a fair number of research grants. The economists argue that transfer limits should be set to maximize system-wide social welfare. Your group has joined their research team in order to provide an engineering-based answer to the question: What is the social-welfare maximizing system design, given the load growth projection and the existing peak load conditions?

Data:

The data file `dWSCC.m` provides the base case data for the system. The program `stable.m` as well as any other component of the MATLAB power systems toolbox can be used to aid in the analysis.

Appendix II– PowerViz Log File

The following is a printout of the power flow log file produced by PowerViz using the data file for the reduced WSCC system.

```
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
++ PowerViz Power Flow Log --------------- Sun Mar 11 17:06:58 2001 ++
++ System Title:                                                     ++
++ System MVA Base:   100                                            ++
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

-------------------------- Island Summary -----------------------------
 18 Active Buses
 31 Lines
 17 Generator Buses
 The swing bus is bus # 8.

------------------ Power Flow Performance Summary --------------------
      |        MW Mismatch            |       MVAr Mismatch
 Iter |    System    | Worst Bus | Bus# |    System    | Worst Bus | Bus#
-----------------------------------------------------------------------
   0  | -6276.7646 | 2338.5973 |   7  |   295.5632 |  295.5632 |   1
   1  |   684.7233 |  450.2689 |   3  |     3.0730 |    3.0730 |   1
   2  |     0.1278 |    0.2228 |   3  |     0.0074 |    0.0074 |   1
   3  |     0.0000 |    0.0000 |  12  |     0.0000 |    0.0000 |   1

----------------------- Generation Summary --------------------------
      | at   | Target |    Solved V    |  Generator Output     | VAr
 Gen# | Bus# | V mag  |  mag  | angle | MW         | MVAr     | Limits
-----------------------------------------------------------------------
   1  |   1  | 1.050  | 1.050 | 73.77 |  8860.00 |  3054.75 |  Off
   2  |   2  | 1.075  | 1.075 | 47.38 | 27268.00 |  5533.70 |  Off
   3  |   3  | 1.030  | 1.030 |  0.61 | 19577.00 |  3017.16 |  Off
   4  |   4  | 1.020  | 1.020 | 24.66 |  5512.00 | -2604.53 |  Off
   6  |   6  | 1.060  | 1.060 | 45.75 |  3563.00 |   744.39 |  Off
   7  |   7  | 1.000  | 1.000 | 15.76 |  1637.00 |   402.27 |  Off
   8  |   8  | 1.040  | 1.040 |  0.00 | 14560.97 |  1153.98 |  Off
   9  |   9  | 1.000  | 1.000 | 50.47 |  2793.00 | -1158.93 |  Off
  10  |  10  | 1.040  | 1.040 | 36.11 |  4911.00 |  1772.92 |  Off
  11  |  11  | 1.010  | 1.010 | 22.66 |  2215.00 |   -92.81 |  Off
  12  |  12  | 1.040  | 1.040 | 21.46 | 13867.00 |  2885.29 |  Off
  13  |  13  | 1.030  | 1.030 | -1.62 |  2376.00 |   119.54 |  Off
  14  |  14  | 1.010  | 1.010 | 43.28 |   212.00 |    60.29 |  Off
  15  |  15  | 1.030  | 1.030 | 34.94 |  2600.00 |  1064.75 |  Off
  16  |  16  | 1.000  | 1.000 | 27.14 |  3563.00 |   794.14 |  Off
  17  |  17  | 0.990  | 0.990 | 37.75 |  2696.00 |   -81.35 |  Off
  18  |  18  | 1.020  | 1.020 | 25.97 |  2985.00 |   495.37 |  Off
```

```
---------------- Calculated Bus and Line-Flow Results ----------------

------------------ Bus #1, Name: BCHydro - Gen Bus -------------------
 Bus Voltage: 1.050 @ 73.77 degrees
 Load: 6300.00 MW + 2800.00 MVAr
 Generation: 8860.00 MW + 3054.75 MVAr
---------------------------- Line Flows ------------------------------
  Line #1 to Bus #2,  Flow: 2258.10 MW + 185.18 MVAr
  Line #6 to Bus #5,  Flow: 301.90 MW + 69.57 MVAr

--------------------- Bus #2, Name: NW - Gen Bus ---------------------
 Bus Voltage: 1.075 @ 47.38 degrees
 Load: 23400.00 MW + 2600.00 MVAr
 Generation: 27268.00 MW + 5533.70 MVAr
---------------------------- Line Flows ------------------------------
  Line #1 to Bus #1,  Flow: -2155.20 MW + 857.76 MVAr
  Line #2 to Bus #3,  Flow: 2900.27 MW + 1083.48 MVAr
  Line #3 to Bus #4,  Flow: 1638.02 MW + 367.49 MVAr
  Line #4 to Bus #4,  Flow: 1527.01 MW + 354.63 MVAr
  Line #7 to Bus #9,  Flow: -134.63 MW + 234.04 MVAr
  Line #8 to Bus #6,  Flow: 92.53 MW + 36.30 MVAr

-------------------- Bus #3, Name: PG&E - Gen Bus --------------------
 Bus Voltage: 1.030 @ 0.61 degrees
 Load: 21800.00 MW + 2200.00 MVAr
 Generation: 19577.00 MW + 3017.16 MVAr
---------------------------- Line Flows ------------------------------
  Line #2 to Bus #2,  Flow: -2659.72 MW + 1313.63 MVAr
  Line #5 to Bus #8,  Flow: 436.72 MW + -496.48 MVAr

------------------- Bus #4, Name: LADWP - Gen Bus --------------------
 Bus Voltage: 1.020 @ 24.66 degrees
 Load: 6200.00 MW + -3300.00 MVAr
 Generation: 5512.00 MW + -2604.53 MVAr
---------------------------- Line Flows ------------------------------
  Line #3 to Bus #2,  Flow: -1568.28 MW + 278.72 MVAr
  Line #4 to Bus #2,  Flow: -1466.41 MW + 249.30 MVAr
  Line #12 to Bus #7,  Flow: 460.91 MW + 49.14 MVAr
  Line #15 to Bus #10,  Flow: -571.84 MW + 56.18 MVAr
  Line #16 to Bus #11,  Flow: 163.53 MW + 31.97 MVAr
  Line #26 to Bus #8,  Flow: 2035.07 MW + 142.15 MVAr
  Line #27 to Bus #12,  Flow: 259.01 MW + -111.98 MVAr

----------------- Bus #5, Name: TransAlt - Load Bus ------------------
 Bus Voltage: 1.031 @ 70.25 degrees
 Load: 300.00 MW + 50.00 MVAr
---------------------------- Line Flows ------------------------------
  Line #6 to Bus #1,  Flow: -300.00 MW + -50.00 MVAr

--------------------- Bus #6, Name: ID - Gen Bus ---------------------
 Bus Voltage: 1.060 @ 45.75 degrees
```

```
 Load: 2800.00 MW + 700.00 MVAr
 Generation: 3563.00 MW + 744.39 MVAr
---------------------------- Line Flows ------------------------------
  Line #8 to Bus #2,  Flow: -92.22 MW + -33.26 MVAr
  Line #9 to Bus #10,  Flow: 855.22 MW + 77.65 MVAr

--------------------- Bus #7, Name: NV - Gen Bus ---------------------
 Bus Voltage: 1.000 @ 15.76 degrees
 Load: 4000.00 MW + 100.00 MVAr
 Generation: 1637.00 MW + 402.27 MVAr
---------------------------- Line Flows ------------------------------
  Line #12 to Bus #4,  Flow: -453.89 MW + 22.27 MVAr
  Line #13 to Bus #10,  Flow: -1577.11 MW + 255.49 MVAr
  Line #14 to Bus #11,  Flow: -332.00 MW + 24.51 MVAr

------------------- Bus #8, Name: SCE - Slack Bus --------------------
 Bus Voltage: 1.040 @ 0.00 degrees
 Load: 19800.00 MW + -1200.00 MVAr
 Generation: 14560.97 MW + 1153.98 MVAr
---------------------------- Line Flows ------------------------------
  Line #5 to Bus #3,  Flow: -435.61 MW + 505.93 MVAr
  Line #17 to Bus #11,  Flow: -1873.69 MW + 746.00 MVAr
  Line #26 to Bus #4,  Flow: -1946.27 MW + 733.86 MVAr
  Line #29 to Bus #12,  Flow: -1122.73 MW + 333.70 MVAr
  Line #30 to Bus #13,  Flow: 139.26 MW + 34.49 MVAr

--------------------- Bus #9, Name: MT - Gen Bus ---------------------
 Bus Voltage: 1.000 @ 50.47 degrees
 Load: 1400.00 MW + -800.00 MVAr
 Generation: 2793.00 MW + -1158.93 MVAr
---------------------------- Line Flows ------------------------------
  Line #7 to Bus #2,  Flow: 136.81 MW + -210.67 MVAr
  Line #10 to Bus #10,  Flow: 712.32 MW + -88.21 MVAr
  Line #11 to Bus #14,  Flow: 543.87 MW + -60.05 MVAr

----------------- Bus #10, Name: PACE(UT) - Gen Bus ------------------
 Bus Voltage: 1.040 @ 36.11 degrees
 Load: 4300.00 MW + 900.00 MVAr
 Generation: 4911.00 MW + 1772.92 MVAr
---------------------------- Line Flows ------------------------------
  Line #9 to Bus #6,  Flow: -839.99 MW + 65.40 MVAr
  Line #10 to Bus #9,  Flow: -694.91 MW + 272.58 MVAr
  Line #13 to Bus #7,  Flow: 1630.20 MW + 321.37 MVAr
  Line #15 to Bus #4,  Flow: 582.82 MW + 59.60 MVAr
  Line #24 to Bus #17,  Flow: -67.12 MW + 153.97 MVAr

----------------- Bus #11, Name: WAPAL.C. - Gen Bus ------------------
 Bus Voltage: 1.010 @ 22.66 degrees
 Load: 0.00 MW + 24.00 MVAr
 Generation: 2215.00 MW + -92.81 MVAr
---------------------------- Line Flows ------------------------------
  Line #14 to Bus #7,  Flow: 335.87 MW + 15.67 MVAr
```

```
  Line #16 to Bus #4,  Flow: -162.93 MW + -26.01 MVAr
  Line #17 to Bus #8,  Flow: 1958.30 MW + 32.38 MVAr
  Line #18 to Bus #12,  Flow: 83.77 MW + -138.85 MVAr

-------------------- Bus #12, Name: AZ - Gen Bus ---------------------
 Bus Voltage: 1.040 @ 21.46 degrees
 Load: 12200.00 MW + 1800.00 MVAr
 Generation: 13867.00 MW + 2885.29 MVAr
---------------------------- Line Flows -------------------------------
  Line #18 to Bus #11,  Flow: -83.23 MW + 144.73 MVAr
  Line #19 to Bus #17,  Flow: -768.91 MW + 330.96 MVAr
  Line #27 to Bus #4,  Flow: -257.31 MW + 128.72 MVAr
  Line #28 to Bus #18,  Flow: -359.31 MW + 145.57 MVAr
  Line #29 to Bus #8,  Flow: 1167.00 MW + 100.04 MVAr
  Line #31 to Bus #13,  Flow: 1968.76 MW + 235.28 MVAr

------------------- Bus #13, Name: SDG&E - Gen Bus -------------------
 Bus Voltage: 1.030 @ -1.62 degrees
 Load: 4400.00 MW + -400.00 MVAr
 Generation: 2376.00 MW + 119.54 MVAr
---------------------------- Line Flows -------------------------------
  Line #30 to Bus #8,  Flow: -138.84 MW + -30.28 MVAr
  Line #31 to Bus #12,  Flow: -1885.16 MW + 549.82 MVAr

--------------- Bus #14, Name: WAPAU.M.(WY) - Gen Bus ----------------
 Bus Voltage: 1.010 @ 43.28 degrees
 Load: 80.00 MW + 40.00 MVAr
 Generation: 212.00 MW + 60.29 MVAr
---------------------------- Line Flows -------------------------------
  Line #11 to Bus #9,  Flow: -537.40 MW + 128.89 MVAr
  Line #20 to Bus #15,  Flow: 669.40 MW + -108.60 MVAr

--------------- Bus #15, Name: WAPAL.M.(CO) - Gen Bus ----------------
 Bus Voltage: 1.030 @ 34.94 degrees
 Load: 2750.00 MW + 600.00 MVAr
 Generation: 2600.00 MW + 1064.75 MVAr
---------------------------- Line Flows -------------------------------
  Line #20 to Bus #14,  Flow: -659.35 MW + 208.66 MVAr
  Line #21 to Bus #16,  Flow: 641.26 MW + 119.12 MVAr
  Line #22 to Bus #17,  Flow: -131.91 MW + 136.97 MVAr

------------------ Bus #16, Name: P.C.CO - Gen Bus -------------------
 Bus Voltage: 1.000 @ 27.14 degrees
 Load: 4700.00 MW + 700.00 MVAr
 Generation: 3563.00 MW + 794.14 MVAr
---------------------------- Line Flows -------------------------------
  Line #21 to Bus #15,  Flow: -632.52 MW + -30.12 MVAr
  Line #23 to Bus #17,  Flow: -504.48 MW + 124.26 MVAr

----------------- Bus #17, Name: WAPAU.C. - Gen Bus ------------------
 Bus Voltage: 0.990 @ 37.75 degrees
 Load: 600.00 MW + 400.00 MVAr
```

```
 Generation: 2696.00 MW + -81.35 MVAr
---------------------------- Line Flows ------------------------------
  Line #19 to Bus #12,  Flow: 790.94 MW + -97.12 MVAr
  Line #22 to Bus #15,  Flow: 133.09 MW + -125.33 MVAr
  Line #23 to Bus #16,  Flow: 513.55 MW + -29.02 MVAr
  Line #24 to Bus #10,  Flow: 68.06 MW + -144.73 MVAr
  Line #25 to Bus #18,  Flow: 590.36 MW + -85.16 MVAr

-------------------- Bus #18, Name: NM - Gen Bus ---------------------
 Bus Voltage: 1.020 @ 25.97 degrees
 Load: 3200.00 MW + 400.00 MVAr
 Generation: 2985.00 MW + 495.37 MVAr
---------------------------- Line Flows ------------------------------
  Line #25 to Bus #17,  Flow: -577.54 MW + 209.98 MVAr
  Line #28 to Bus #12,  Flow: 362.54 MW + -114.61 MVAr
```