Study of FACTS/ESS Applications in Bulk Power System

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(ABSTRACT)

The electric power supply industry, with more than 100 years history, has evolved into one of the largest industries. Secure and reliable operation of the electric power system is fundamental to economy, social security and quality of modern life. The complicated power grid is now facing severe challenges to meet the high level secure and reliable operation requirements, which includes lack of transmission capability, restraints by a competitive market environment, and power infrastructure vulnerability.

New technologies will play a major role in helping today's electric power industry to meet the above challenges. This dissertation has focused on some key technologies among them, including the emerging technologies of energy storage, controlled power electronics and wide area measurement technologies. Those technologies offer an opportunity to develop the appropriate objectives for power system control.

In bulk power transmission systems, the use of power electronics based devices with energy storage system integrated into them, such as FACTS/ESS, can provide valuable added benefits to improve stability, power quality, and reliability of power systems. There is a lack of scientific mechanisms to guide their technical decisions making process, even though many electric utilities in the U.S. an all over the world are beginning to implement FACTS/ESS for many different applications. The study in this dissertation has provided several guidelines for the implementation of FACTS/ESS in bulk power systems.

The interest of this study lies in a wide range of FACTS/ESS technology applications in bulk power system to solve some special problems that were not solved well without the application of FACTS/ESS. The special problems we select to solve by using FACTS/ESS technology in this study include power quality problem solution by active power compensation, electrical arc furnace (EAF) induced problems solution, inter-area mode low frequency oscillation

suppression, coordination of under frequency load shedding (UFLS) and under frequency governor control (UFGC), wide area voltage control.

From this study, the author of this dissertation reveals the unique role that FACTS/ESS technology can play in the bulk power system stability control and power quality enhancement in power system. In this dissertation, almost all the studies are based on the real system problems, which means that the study results are special valuable to certain utilities that have those problems.

By the theoretical and fundamental research in this study, we have achieved thorough understanding of power system responses to dynamic active power injection/absorption, comprehensive characterization of different energy storage technology applications. The study in this dissertation can assist power industry choose the right FACTS/ESS technology for their intended functions, which will improve the survivability, minimize blackouts, and reduce interruption costs through the use of energy storage systems.

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To my beloved family

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Chapter 1. Introduction

Secure and reliable operation of the electric power system is fundamental to economy, social security and quality of modern life, because electricity has become a basic necessary in modern society. The way of modern life depends upon efficient and reliable electrical energy. The reliable and efficient electrical infrastructure provides the supporting to all economic and societal progress.

Because of the financial constraints, environmental considerations and deregulation constraints, the electric power system is now facing with difficult technical problems in meeting the basic power quality requirement to provide all the consumer electricity supply with the requirement of power quality. Higher loading in the power grid will be the certain result, reducing the reliability and security of the operation of power system. The industry is facing new economical and social pressures to refocus its business so as to meet the energy needs of the society in a way that is "sustainable" in a long run. The challenges to the industry are to: (1) produce, transmit and use energy in an environmentally responsible manner, (2) reduce costs by improving operating efficiency and business practices, and (3) enhance the reliability and quality of power supply [1, 6, 7, 9, 10, 11, 13].

The electric power industry has gone through many changes in the past several years. There are several major trends in the U.S. electric power industry today showing as follows [3, 9, 12, 14, 16]:

- Slow-down of deregulation legislation
- Change of electricity generation and transmission ownership
- Limitation of transmission system expanding
- Pressure from environmental requirement
- Competition in electric power market

Meanwhile, more and more efforts from both researchers and utilities are focusing in the new technologies that help the power system with long history to meet the new challenges. Those technologies are playing and will play very important role for improving the reliability and security of power system operation. Those new technologies provide an opportunity for overcoming the difficulties facing the power industry with low cost developments to better utilize the available resources. Those technologies could be combined within a comprehensive control structure to benefit the entire power grid. However, social factors should be considered while applying those new technologies [4, 5].

1.1 Current Challenges to Electric Power Industry

The electric power supply industry, with its humble beginning in the 1880s, has evolved into one of the largest industries. The North American power network is considered to be the largest and most complex machine in the world. The North American power network within its transmission lines connects all the electric generation and distribution on the continent. The whole network include 15,000 generators in 10,000 power plants, and hundreds of thousands of miles of transmission lines and distribution networks, whose estimated worth is over US$800 billion. This complicated power grid is now facing severe challenges to meet the high-level secure and reliable operation requirements [1, 2, 7].

Lack of Transmission Capability

According to the study of Electric Power Research Institute (EPRI), over the next ten years, demand for electric power is expected to increase by about 25% while under the current plans the electric transmission capacity will increase only by 4%. This shortage of transfer capability can lead to serious congestion of the transmission grids. Fig. 1-1 to Fig. 1-2 show how much the electric transmission system does not meet the requirement for the need of electric power consumption [1, 2].

According to the shortage of transmission capability, many transmission lines will be heavily loaded and large amount of load will be transferred through long distance, with many more bottlenecks showing up. The more and more stressing structure will be the most dangerous factors causing power system stability problems. The lower generation margin will reduce the ability of power system to face emergent situations [1, 2].

With more long-distance power transfers, no single existing control center can perform contingencies analysis for entire interconnection. As interconnection models with 40,000 buses, 50,000 lines, and 3000 generators, the reliable operation requires an operating point that satisfies more than 2 billion constraints [1, 2].

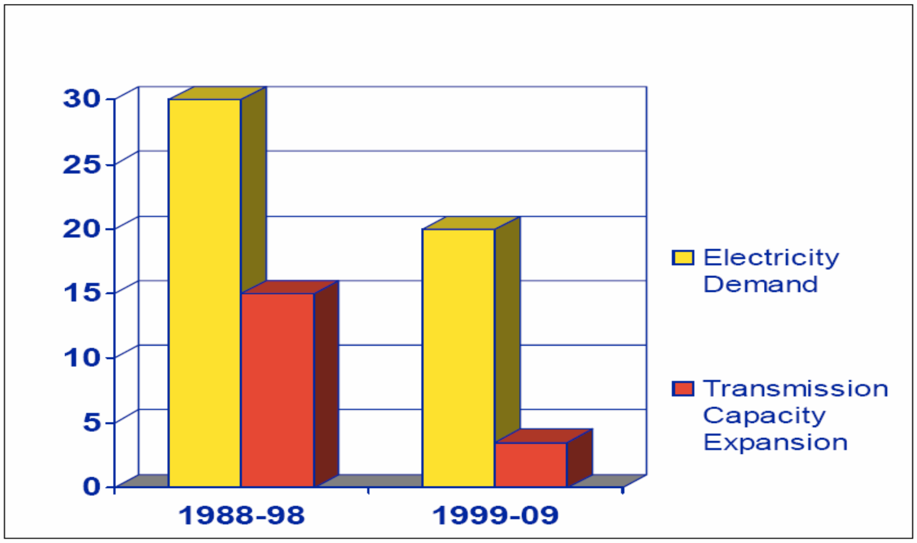


Fig. 1-1. Transmission additions in the US [1] (Massoud Amin)

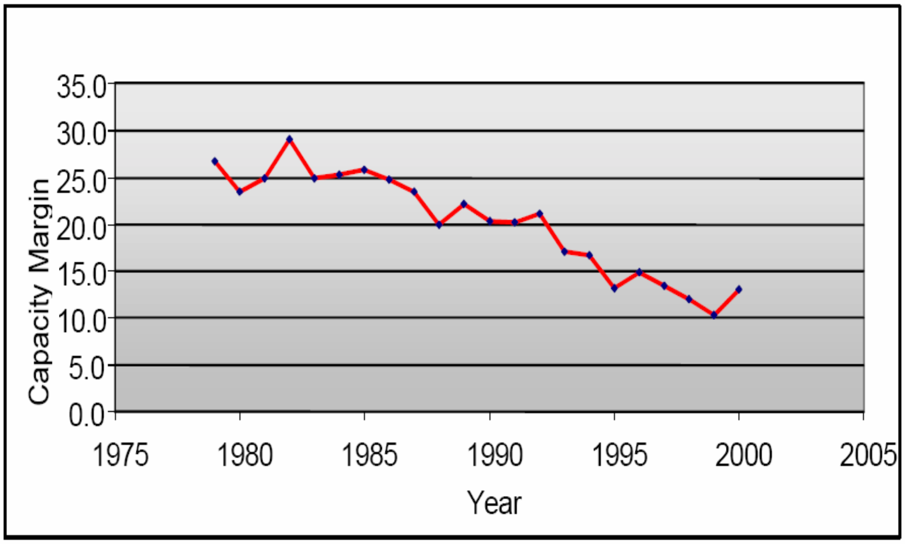


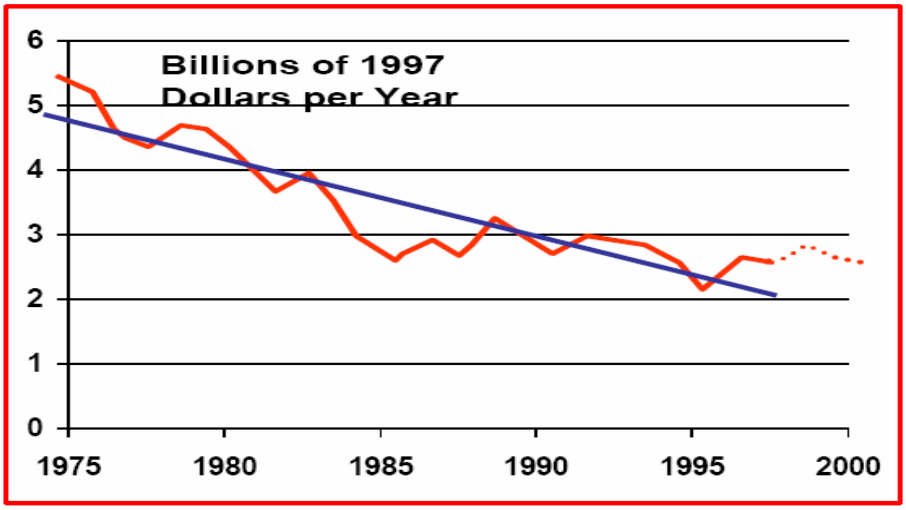
Fig. 1-2. Generation capacity margin in North America [1] (Massoud Amin)

Restraints by a Competitive Market Environment

Another important dimension is the effect of deregulation and economic factors to a particular infrastructure. The electric power industry has changed significantly since the Federal Energy

Regulatory Commission (FERC) started to encourage the development of competitive markets for wholesale power trading through deregulation of portions of the electric power industry [2, 4, 17].

Historically the emphasis of the electric power industry was on reliability and security at the expense of economy, because this industry was a non-competitive, regulated monopoly industry, with the goal to deliver power from generation center to load areas reliably and economically. Traditionally, new delivery capacity would be added to handle load increases, but because of the current difficulty in obtaining permits and the uncertainty about achieving and adequate rate of return on investment, total circuit miles added annually are declining while total demand for delivery resources continues to grow, which is shown in Fig. 1-3 [1]. In recent years, actual demand in the U.S., as an example, has increased some 35%, while capacity has increased only 18%. The network is becoming increasingly stressed, and whether the carrying capacity or safety margin will exist to support anticipated demand is in question [2].



Source: Electric Perspectives, July/August 2001

Fig. 1-3. Transmission Investment from 1975 to 2000 [1] (Massoud Amin)

The complex systems used to relieve bottlenecks and clear disturbances during periods of peak demand are at great risk to serious disruption, creating a critical need for technological improvements. Challenges include developing and deploying active-control high-voltage devices to enable increased power throughput; and ensuring system stability, system reliability, robustness, and efficiency in the competitive marketplace. The competitive market environment makes utilities hesitate to invest in the facilities shown in Fig. 1-4 [1, 2].

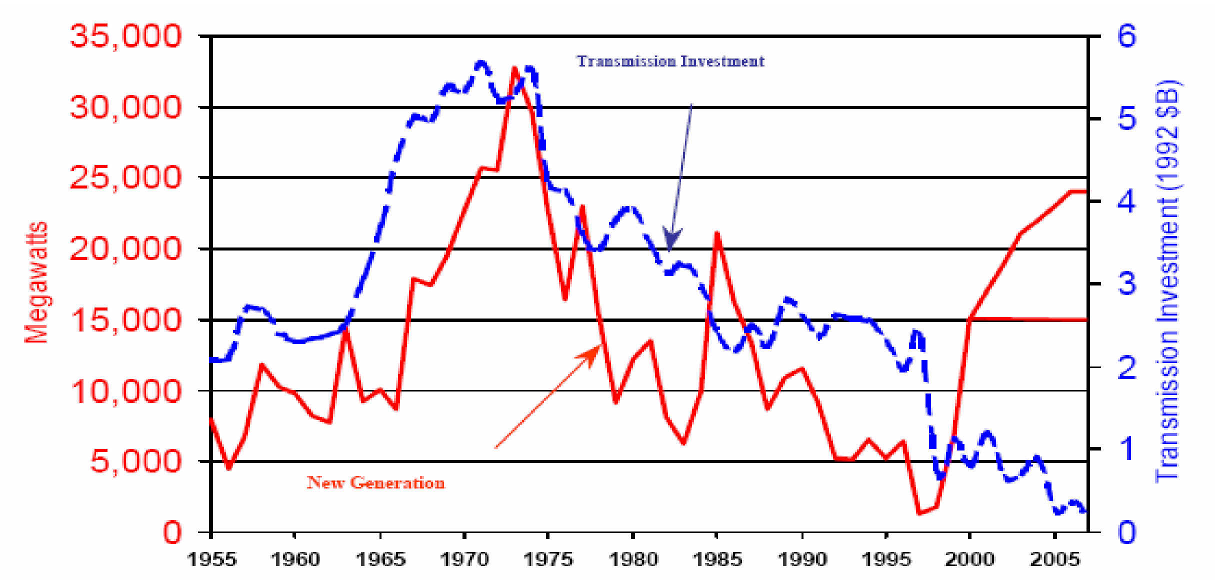


Fig. 1-4. The efficiency of investment of transmission facility [1] (Massoud Amin)

Power Infrastructure Vulnerability

With more than 100 years of history, the power grid is a vulnerable infrastructure because of the complexity and aging equipments in the system. The power infrastructure is vulnerable to physical and cyber disruption. The sources of vulnerability include natural disasters (e.g., earthquakes), equipment failures, human errors, or deliberate sabotage and terrorist attacks, shown in Fig. 1-5. As the power grids become heavily loaded with long distance transfers, the already complex system dynamics become even more vulnerable. In a vulnerable system, a simple incident such as an equipment failure can lead to a cascaded sequence of events, leading to widespread blackouts [1, 14].

Even though technologies may meet the demand, but the investments on the new technologies developments and applications are discouraging because of the uncertainties on return rate of investments.

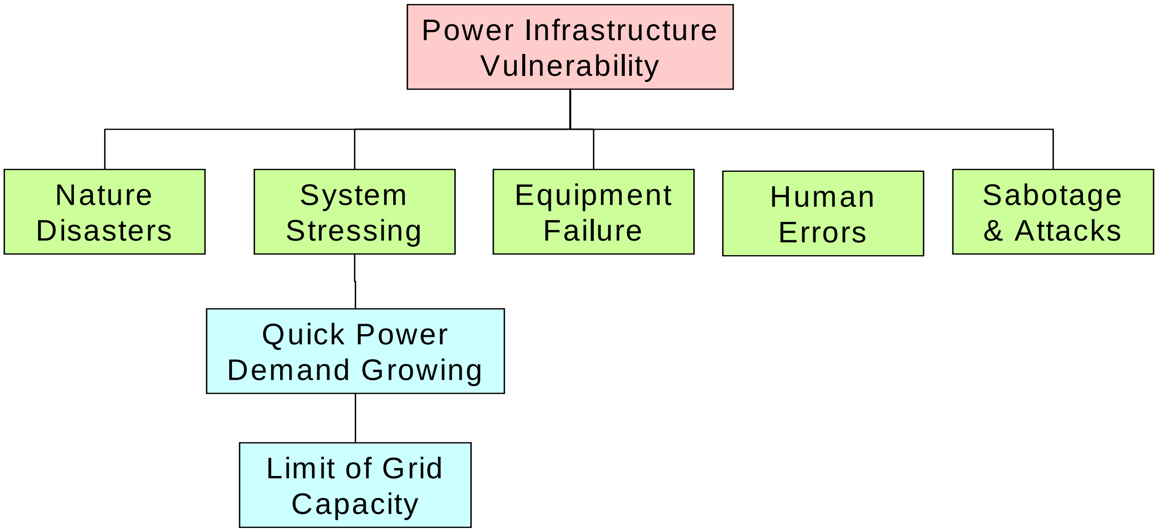


Fig. 1-5. Power infrastructure vulnerability

Even though modern societies cannot function without a secure supply of electric energy, but the power supply is becoming increasingly vulnerable because of customer demand, natural disasters, and a new threat of terrorism. In the year 2003, many major power systems experienced the disaster of blackouts, which is shown in Fig. 1-6, including the massive August 14th, 2003 North America blackout [4, 8].

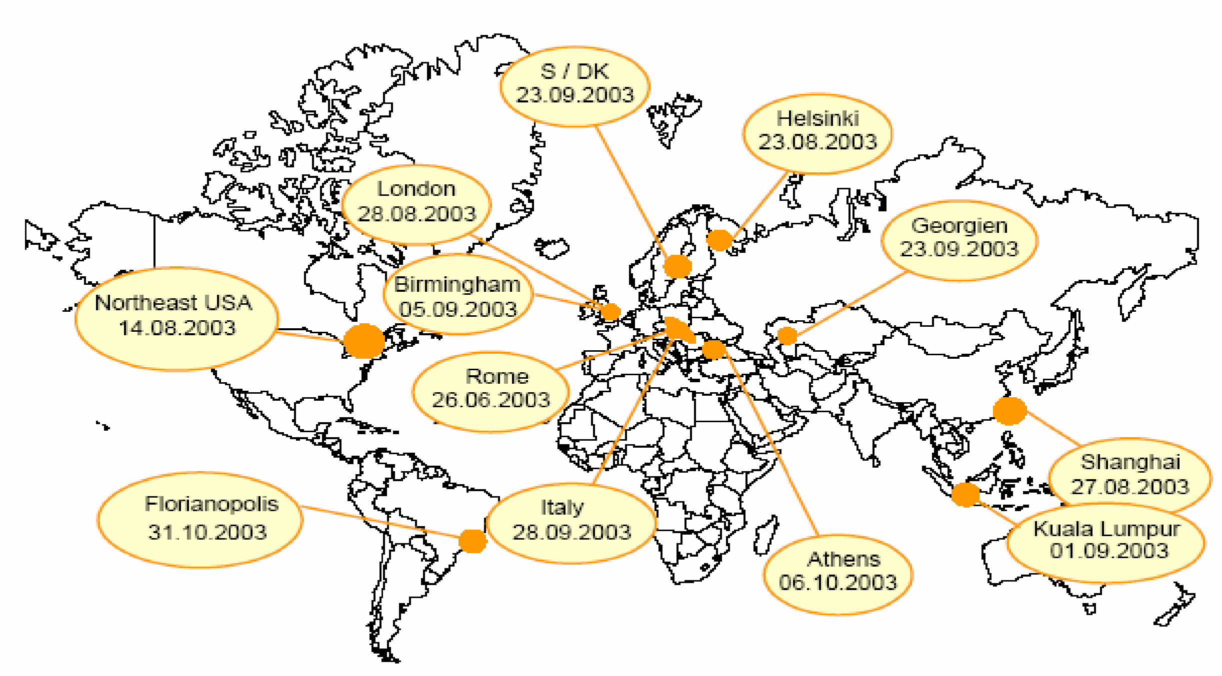


Fig. 1-6. Major blackouts happened in the year 2003 [4] (Michael Bahrman)

The massive August 14th 2003 North American Blackout, shown in Fig. 1-7 [18], impacted approximately 50 million persons. Cost estimates of these blackouts range from $6B+ in the US according to the Wall Street Journal. The cascading blackouts were sudden illumination of our electricity infrastructure's vulnerabilities.

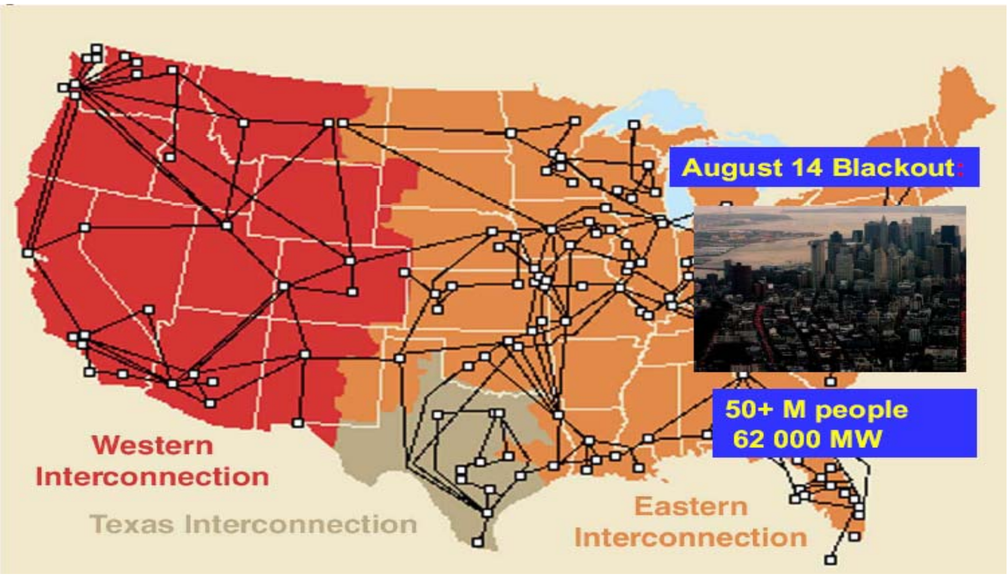


Fig. 1-7. August 14th, 2003 blackout in North America [18] (Aty Edris)

1.2 New Technologies for Meeting Challenges

A wide range of new technologies is likely to play a major role in meeting the challenges and shaping the future directions of power systems. In response to the above challenges, several enabling technologies and advances are/will be available that can provide necessary capabilities when combined in an over-all system design. Some of the enabling technologies being developed by industry [5, 15] are shown in Fig. 1-8.

Symptomatic of the system control difficulties have been the increasing number of blackouts throughout the world, many due to system voltage instability. This emphasizes the need for a new direction in power system control for overcoming the present technical difficulties as well as gaining economies for the power utilities. Among them are the following key technologies that are within this study. Emerging technologies of energy storage, controlled power electronics and wide area measurement technologies offer an opportunity to develop the appropriate objectives for power system control.

- Flexible AC Transmission System (FACTS) devices, which are high-voltage thyristor-based electronic controllers that increase the power capacity of transmission lines and have already been deployed in several high-value applications. At peak demand, up to 50 percent more power can be controlled through existing lines.
- Wide-Area Measurement Systems (WAMS), which integrate advanced sensors with satellite communication and time stamping using global positioning systems (GPS) to detect and report angle swings and other transmission system changes.
- Distributed resources such as small combustion turbines, solid oxide an other fuel cells, photovoltaics, superconducting magnetic energy storage (SMES), transportable battery energy storage systems (TBESS), etc.

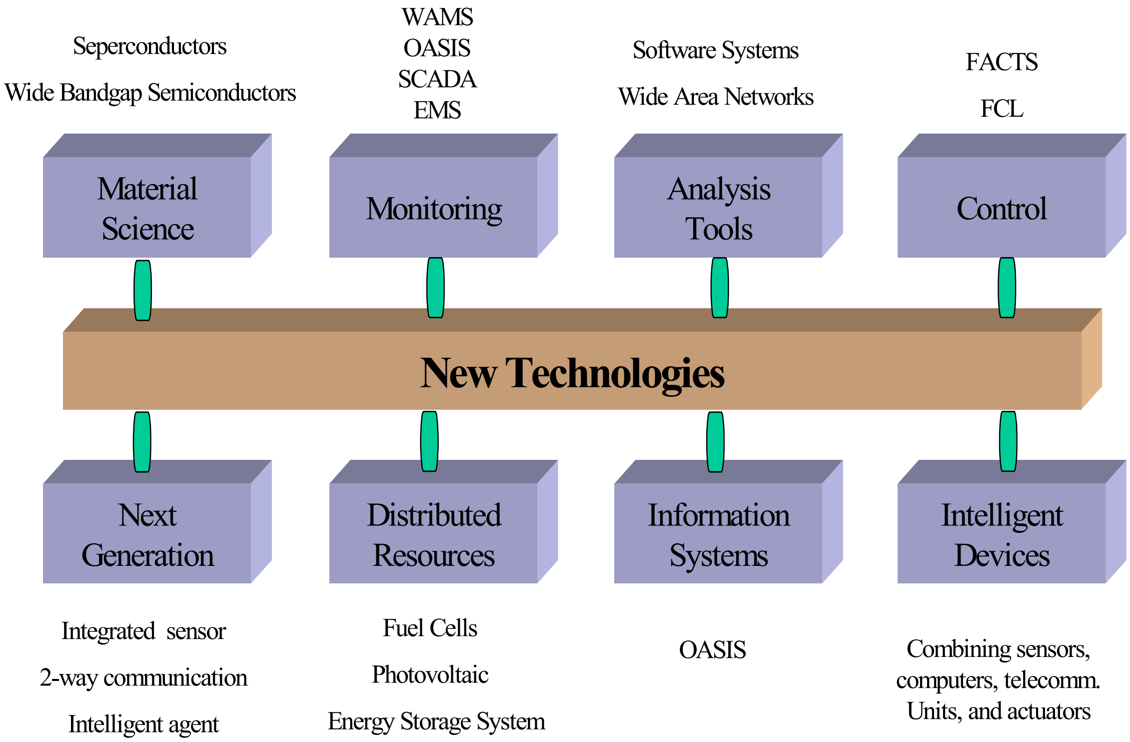


Fig. 1-8. New technologies under development

In the coming decades, electricity's share of total energy in the world is expected to continue to grow, as more efficient and intelligent processes are introduced into this network. For example, controllers based on power electronics, combined with wide-area sensing and management systems have the potential to improve situational awareness, precision, reliability and robustness of this continental-scale system. It is envisioned that the electric power grid will move from an electro-mechanically controlled system into an electronically controlled network in the next two decades.

Synchronized Phasor Measurements (PMU) were introduced in mid-1980s. Since then, the subject of wide-area measurements in power systems using PMUs and other measurement instruments has been receiving considerable attention around the world. From the early prototypes of the PMU built at Virginia Tech, a large number of commercial products have been installed at various locations around the world. Even though wide area measurements were first introduced in power systems as inputs for static state estimators, this technology has more interesting applications in system control.

In bulk power transmission systems, the use of power electronics based devices can potentially overcome limitations of the present mechanically controlled transmission system. These flexible networks help delay or minimize the need to build more transmission lines and enable neighboring utilities and regions to economically and reliably exchange power.

Integrating an energy storage system (ESS), such as battery energy storage systems (BESS), superconducting magnetic energy storage (SMES), flywheel energy storage, or supercapacitor energy storage, into a voltage source converter (VSC)-based FACTS device can lead to improved controller flexibility by providing dynamic decentralized active power capabilities. Combined FACTS/ESS can improve power flow control, oscillation damping, and voltage control easily and economically.

1.3 The Objective and Contributions of the Dissertation

1.3.1 The Purpose of the Study

As transmission systems become increasingly stressed, utilities have begun to consider FACTS devices as possible solutions to mounting problems. Energy storage systems are further being investigated as a means to provide additional flexibility. Multiply the number of integrated FACTS/ESS systems by the possible number of power system problems (voltage support, oscillation damping, transmission congestion, etc) and the range of applications expands significantly. Unfortunately the breadth and depth of knowledge and expertise do not currently exist to allow utility engineers to make informed decisions to match available technologies with the system problem(s) they are addressing.

According to the study of EPRI and DOE, without a major shift in the way the energy system is planed, built and operated, the U.S. will invest hundreds of billions of dollars in conventional electric infrastructure over the next 200 years to meet expended growth. Minimizing the cost of new electric infrastructure is a key to strengthening the economy. In bulk power transmission systems, the use of power electronics based devices like the FACTS and energy storage system in this study, can potentially overcome limitations of the present mechanically controlled transmission system. Application of those technologies (FACTS, ESS, and wide area measurement technology like FNET) can improve the limitation of transporting of electric power of the existing transmission systems in the more safe and reliable way. These flexible networks help delay or minimize the need to build more transmission lines and enable neighboring utilities and regions to economically and reliability exchange power.

The interest of this study lies in a wide range of FACTS/ESS technology applications in bulk power system to solve some special problems that were not solved well without the application of FACTS/ESS. In this dissertation, the application of FACTS/ESS based on wide area measurement technology is also a focus of this study. The special problems we select to solve by using FACTS/ESS technology in this study include power quality solution by active power compensation, electrical arc furnace (EAF) induced problems solution, inter-area mode low frequency oscillation suppression, coordination of under frequency load shedding (UFLS) and under frequency governor control (UFGC), wide area voltage control, etc.

From this study, the author of this dissertation reveals the unique role that FACTS/ESS technology can play in the bulk power system stability control and power quality in power system. In this dissertation, almost all the studies are based on the real system problems, which means that study results are special valuable to certain utilities that have those problems.

By the theoretical and fundamental research in this study, we will achieve thorough understanding of power system responses to dynamic active power injection/absorption, comprehensive characterization of different energy storage technologies with the corresponding power electronic interfaces, comparison of different storage systems with respect to typical applications. The immediate objective is to assist power industry choose the right FACT/energy storage technology for their intended functions. The ultimate objective is to improve the survivability, minimize blackouts, and reduce interruption costs through the use of energy storage systems.

1.3.2. Contributions of the Dissertation

The ultimate objective of this study is to improve the survivability of electric power systems and minimize the number of blackouts using cost effective methods as a result of work in this dissertation. Electric power systems are one of critical infrastructures. Interruptions accumulate large direct costs, huge indirect economic costs, and immeasurable social impact.

Active Power Compensation

It is easily understood that reactive load can cause power quality problems associated with voltage. Traditionally, for a mainly inductive supply system, power quality can be improved by using reactive power control methods. For example, power electronics devices like SVC and STATCOM have been able to solve the power quality problems in distribution and transmission systems by controlling reactive power. But for the power quality problem induced by the real load, only adjusting reactive power is not enough.

Real load can not only cause the voltage drop but also the angle variation at the critical buses. These phase angle variations and active power fluctuations can bring stability problems in the bulk power systems. Even the shaft angle of the generators in the nearby system oscillates because of the pulsing active load. That could be harmful to the generator shaft and may reduce the life of generator dramatically. There is a need to study the impact of active load, like the pulsing active load, on the bulk power system.

Advances in both energy storage technologies and the necessary power electronics interface have made energy storage systems (ESS) a viable technology for high power utility. The power industry's demands for more flexible, reliable and fast active power compensation devices make the ideal opportunity for ESS applications. ESS makes it as a possibility to use active power compensation in solving the power quality problems caused by active load.

In this study the author examined the effects of active and reactive load on the power quality in bulk power system. The focus of this study is the impact of active and reactive load on the PCC bus voltage and the operation of the generators in the vicinity system. The study results show that the impacts of active and reactive load on the power quality problems are different. Same amount of active load can cause more angle fluctuation than reactive load. On the other hand, same amount of reactive load can bring more voltage flicker than active load. This study also attempts to find the role of pure active power compensation in correcting the periodic active and reactive load induced problems in a bulk power system. The effect of pure reactive power compensation for the same situation is also studied. The author analyzed how active load operation can affect a power system voltage by giving a detailed discussion about the function of X/R ratio. The simulation results show that either the pure active or pure reactive power compensation method has its own limitation in solving the power quality problems caused by both the active and reactive load. The coordination of both active power compensation and reactive power compensation is an ideal method to solve the power quality problems caused by the combination of active and reactive load. In this situation, FACTS/ESS can provide significant improvements in mitigating this kind of problems over more conventional compensation methods, e.g. STATCOM, because of its active and reactive power control capability.

EAF Induced Problems Solution

The operation of an arc furnace does not only generate harmonics, but also voltage dips. Both the harmonic currents and voltage flickers caused by the operation of an EAF can affect the operation of other equipment or machines in the same factory or nearby factories in the same distribution system. Several studies reported voltage flickers from the operation of an EAF on the power feeders in nearby factories. The studies also discovered that the neighboring distribution network inherently resonated with active oscillation. As mentioned above, instantaneous fluctuations with large amplitudes of active and reactive power in EAF's are sources of power quality disturbances in an electric power system. Traditionally, for a mainly inductive supply system, power quality can be improved by using reactive power control methods. But for the EAF load, only adjusting reactive power is not enough. Real power fluctuation can cause phase angle variations at critical buses. These phase angle variations and active power fluctuations can cause damage to nearby generators.

In this study, the problems caused by the operation of an EAF in a bulk power system have been studied. The author analyze the exact reason why the real power drawn from an EAF can affect a power system, especially the neighboring system that is connected to it, by giving a detailed discussion of the role of X/R ratio. The author studied the solutions for the EAF problem by FACTS/ESS. The study results show that reactive power compensation alone can deal very well with the voltage problem. The reactive power cannot solve the problems about the angle fluctuation and power fluctuation. The active power compensation can be a very good solution for the problems of angle oscillation and power fluctuation induced by the operation of electrical arc furnace. The study shows that the energy storage systems can provide significant improvements in mitigating EAF induced problem over more conventional compensation methods, e.g. STATCOM, because of its active power control capability.

The purpose of introducing energy storage in this case is not for the voltage improvement though this is possible because of the low X/R ratio (X/R≈3). More importantly, the ESS is essential in reducing real power (or angle) oscillations caused by EAF. Many earlier studies have shown that the pulsing load in an EAF could be very harmful to the generator shaft and may reduce the life of generator dramatically. Dynamic active power compensation as offered by FACTS with ESS may offer the ideal solution.

X/R Ratio in Real Bulk Power System

X/R ratio is very important when we study the effect of active and reactive load on the voltage and angle fluctuation in power system. The voltage effect of active power drawn by an EAF is reflected by the real part of system impedance (Thevenin Impedance) R_n. A very common mistake is to assume that in the power system, the X/R ratio is large enough to omit the voltage drop caused by the active load. An incorrect approach to calculating X/R ratio is by considering only the upper transformer or branch. Using this approach one will certainly arrive at a X/R of over 10. According to this study, the correct approach is by looking at all of the parameters including the load in the whole system. In other words, the R and X are not proportional to the impedance of the upper transformers and lines; instead they should be the Thevenin Impedance seen from the PCC bus of the entire system. From the simulation results in this study, we can see that the active load plays an important role on the bus voltage drop. A practical simulation X/R ratio identification method was proposed in this study. The PSS/E software has the ability to calculate the Thevenin Impedance automatically if the zero and negative sequence impedance are available. With a sample 23-buses sample system provided by PTI was used in this study, the X/R ratio results calculated by the both methods are identical.

Inter-area Mode Low Frequency Oscillation Mitigation in Bulk Power System

Low frequency oscillations in some parts or between parts of the interconnected power systems are commonly experienced. The low frequency oscillations take place as synchronous generators swing against each other. The frequency range of these oscillations is from 0.1 to 2.5 Hz, related to the dynamic power transfer between areas. At times the oscillations may continue to grow, causing instability. There are two types of oscillations, referred to as local mode and inter-area mode, corresponding to a single-machine-to-infinite-bus structure and the interconnected power systems respectively.

Although a number of alternatives are available for damping low frequency oscillations in power systems, the power system stabilizer (PSS) is the most commonly used option. It operates by generating an electric torque in phase with the rotor speed. In most cases, the PSS works well in damping oscillations. However because the parameters of PSS tuned to fixed parameters its control has less flexibility, which means the control result is far from ideal if the operating conditions and/or structures of the system change.

Other modern controllers used to damp power system oscillation may include high-voltage dc (HVDC) lines, static var compensators (SVCs), thyristor-controlled series capacitors (TCSCs), and other flexible ac transmission system (FACTS) equipment. FACTS devices, especially STATCOMs, have the advantage of flexibility of location to achieve the best control results.

In this study, the author studied the inter-area mode power system low frequency oscillation by analyzing the low frequency oscillation phenomena in Nashville area of the TVA system. This oscillation is an inter-area mode oscillation. There are 4 groups of generators at 4 different locations within this area. Generators swing against those in other groups. In each group, generators do not swing against each other, having the same dynamic trends. The author designed both the concentrated and distributed FACTS/ESS controllers and use local generator speed deviation as one of the inputs to damp the low frequency oscillation in Nashville area. For the distributed FACTS/ESS solution, each distributed FACTS/ESS is installed at the location where one-group generators are located. The active and reactive power controls of FACTS/ESS are independent. The active power of FACTS/ESS is controlled to damp the local low frequency oscillation. Reactive power of FACTS/ESS is controlled to keep the local voltage at a standard level. For comparison, the author studied the control effects of different capacity FACTS/ESS. The results show that better control result will be achieved when adequate capacity devices are used.

Coordination of UFLS and UFGC

One of the most undesirable conditions for power system operation is the loss of generator units or transmission lines causing big power-load unbalance. This kind of unbalance will cause the drop of power system frequency from its steady state. If not properly counteracted, it can lead to major stability problems. The typical protection scheme for such conditions is under frequency load shedding (UFLS) to stop the frequency drop after generation-load unbalance happens. UFLS is a final action to mitigate the severe consequences. Load shedding is accomplished by frequency sensitive relays. The relays measure the frequency and rate-of-change of frequency to disconnect load. UFLS is usually implemented in several stages with each stage to shed a particular amount of load at its frequency setting point.

In most of power systems, some spinning reserve is designed to stop the frequency dropping in the emergency situations. Under Frequency Governor Control (UFGC) is designed to activate this spinning reserve when frequency is dropping to a certain level. In most severe generation-load unbalance conditions, the frequency drops so quickly that the governor cannot fully activate spinning reserve. Most of the time, UFLS serves as a tool to prevent the system collapse before governor can fully activate spinning reserve quickly enough to restore the system to its normal operating frequency. This may results in over-shedding. The UFGC cannot help to prevent system from collapse by activating system reserve quickly because of its inertia. UFLS happens before UFGC has the time to take full action. Unfortunately, no method exists to coordinate these two functions before the study in this dissertation.

As an example of energy storage system (ESS) technology, D-SMES system has the advantages in both energy storage ability and flexibility of its power electronics interface. D-SMES has been employed due to its capability to work as active and reactive power generation and absorption systems. The application of D-SMES can provide a direct way to coordinate the UFLS and UFGC. It can help to fully activate the system spinning reserve, which can prevent over shedding. The application of D-SMES can coordinate the UFGC and UFLS to achieve the goal of full activating the spinning reserve and minimizing shedding load. The reason for using the D-SMES rather than the one concentrated SMES is to coordinate with UFGC locally.

By using a 23-buses PTI sample system in this study, the author studied the coordination of UFLS and UFGC by application of D-SMES. The active and reactive power controls of D-SMES are independent. The active power is controlled to stop the dropping of system frequency and the reactive power is control to stabilize the local voltage. The research results show that D-SMES can slow the quick drop of system frequency and hold for the full activation of system spinning reserve. That can help the governors output their maximum reserve before UFLS drops more load which results in minimized load shedding. That means the saving of a lot of money both to the utilities and electricity consumers. This is the first time that UFLS and UFGC can be coordinated well in power system frequency control, by which almost full power system spinning reserve can be used in the frequency emergency situations.

Wide Area Voltage Control in Bulk Power System

In this study, the steady state analysis and dynamic analysis of the voltage problems as well as the control options of the Knoxville area system of TVA are conducted. Comparing the data in load flow, there is a reactive power deficiency in this system and the system is heavily loaded with very little generation reserve. There is potential voltage collapse, in this system according to analysis.

Various near-term options were modeled and tested to find the best technical solutions solving the Knoxville area voltage problem. The options include two pairs of 84 MVAR capacitor banks solution, 300 MVA SVC solution, 300 MVA STATCON solution and installation of various numbers of D-STATCON devices. We also tested the solutions of 550, 700 MVA SVC and 550, 700 MVA STATCON solutions. The effects of the different options are analyzed. For the same VAR rating of different centralized compensation equipments such as Capacitor Banks, SVC and STATCON, the STATCON plays a better role in speeding up the voltage recovery than the other two options.

The rating of two pairs of 84 MVAR Capacitor Banks and 300 MVA, 550 MVA SVC and STATCON cannot satisfy the total reactive power demand of the Knoxville area system. The rating of 700 MVA for SVC and STATCON should be sufficient according to the simulation results.

In this study, the special problem is the low voltage in the 69 kV subtransmission system and 13.8 kV distribution system in this study area. Using all the centralized compensation methods mentioned above, the voltage of 69 kV subtransmission system and 13 kV distribution system cannot be improved to the acceptable level. It should be much more concerned for the voltage control of the subtransmission system in Knoxville area in TVA. Unlike the active power, the reactive power should not be transmitted over a long distance. Load center voltage levels can only be controlled by nearby reactive power sources. For the large and complicated system such as TVA, the distributed compensation is a preferable option. For the complicated network structure of the research region system, the D-STATCON will play a better role in solving the low voltage problems of the 69 subtransmission and 13 kV distribution systems. To prevent the potential voltage collapse in this area, an Under Voltage Load Shedding (UVLS) scheme was designed.

1.4 Organization of the Dissertation

The remainder of this dissertation is organized as follows. Chapter 2 provides an extensive literature review of the FACTS and energy storage system technology applications in bulk power system, especially the categories of different FACTS and ESS technologies and their special application in bulk power system. Chapter 3 to Chapter 6 discuss typical and important applications of FACTS and ESS in the bulk power system to improve the reliability of power system. Chapter 3 discusses the FACTS/ESS applications in the power quality control in power system by the real application example to mitigate the electric arc furnace induced problems by both active power and reactive power compensation. In this chapter, the study is based on a real project in which FACTS/ESS is used in TVA system to solve the power quality problems induced by a 40 MVA electric arc furnace located at Hoeganaes in TVA system. The special active power compensation effect of FACTS/ESS is thoroughly discussed. X/R ratio has been presented to explain why the active power compensation can also control the system voltage. Finally, the control effects of different capacity FACTS/ESS solving the EAF induced both power quality and stability problems have been proposed. In chapter 4, the low frequency oscillation in power system has been analyzed theoretically. A real inter-area low frequency oscillation happened in TVA system within the Nashville area was studied and the mitigation method by FACTS/ESS was proposed. The control results of FACTS/ESS to solve the inter-area mode low frequency oscillation are good especially by using the distributed FACTS/ESS devices within the study area. In chapter 5, coordination of under frequency load shedding scheme and under frequency governor control, which remained as an unsolved problem for a long time, has been discussed by the using of FACTS/ESS especially distributed FACTS/ESS technology. This is the first time that UFLS and UFGC can be coordinated well in power system frequency control, by which almost full power system spinning reserve can be used in the frequency emergency situations. This study can contribute a great deal in finance to electric power industry. The potential of a new wide area monitoring technology application in this study, which is called Frequency Monitoring Network (FNET), has been discussed in this chapter as well. In chapter 6, the application of FACTS and distributed FACTS to solve a real voltage problem within a wide area power system has been discussed. The under voltage load shedding technology application in this study was also analyzed. Based on the studies in the above chapters, a conclusion has been deduced in chapter 7 including some important future study ideas.

Chapter 2. Overview of FACTS and Energy Storage Technologies

2.1 Introduction

Transmission systems are being pushed closer to their stability and thermal limits while the quality of power delivered is greater than ever, because changes are continuously being introduced to a once predictable and monopoly business due to the ongoing expansion and growth of the electric industry including deregulation. Traditional solutions to upgrade the transmission system, which have been primarily in the form of new transmission lines, substations, and associated equipment, are becoming difficult mainly because of the process of permit as explained in Chapter 1. FACTS technologies provide advanced solutions as cost-effective alternatives to new transmission line construction [36-40].

Power electronics based equipments, called Flexible AC Transmission Systems (FACTS), provide technical solutions to address the new operating challenges being presented today, by improving utilization of the existing power system through the application of advanced control technologies. FACTS technologies allow for improved transmission system operation with minimal infrastructure investment, environmental impact, and implementation time compared to the construction of new transmission lines, offering utilities and industry the ability to: (i) Dynamically control power flows on specific transmission and distribution routes, (ii) allow secure loading of transmission and distribution lines to their full thermal capacity, and (iii) improve power quality [33].

The main driving forces for implementing power electronic technology into the electrical networks are [35]:

- The liberalization and resulting competition in the energy market.
- Economical utilization of lightly loaded network lines
- E-commerce in the energy supply industry
- The call for a sustainable society with renewable and distributed resources.
- Utilizing installed network and generating assets better.
- Flexibility required in electrical customers and tariff structures
- Price reduction of power electronic converters and devices.

At present, energy storage advanced solutions are a feasible alternative to decrease the generation reserve and to improve the primary frequency control (PFC). By using proper energy storage systems (ESS), excess energy may be stored to substitute the generation reserve. The breakthrough of these technologies makes possible their incorporation into the power system. In this way, it is feasible to combine the new ESS, such as superconducting magnetic energy storage (SMES), super capacitors (SC), flywheels (FES), and flow batteries (FB), with power converter-based FACTS devices with the purpose of controlling the power system operation and consequently greatly influence the system security [19-23].

The integration of energy storage system (ESS) into FACTS devices, however, may lead to a more economical and/or flexible transmission controller. The enhanced performance will have greater appeal to transmission service providers by providing proven solutions to the problems of uneven active power flow, transient and dynamic stability, subsynchronous oscillations, and power quality issues using active power control. Power conversion systems required for ESS are similar to the power electronics topologies of FACTS devices; a combined FACTS/ESS system can have a comparable cost and provide better performance than separate stand-alone ESS or FACTS devices [20, 22, 23, 24, 31].

Fig. 2-1 shows the general topology of FACTS/ESS controller. Without energy storage part, the whole equipment will behave like a pure traditional FACTS controller [28].

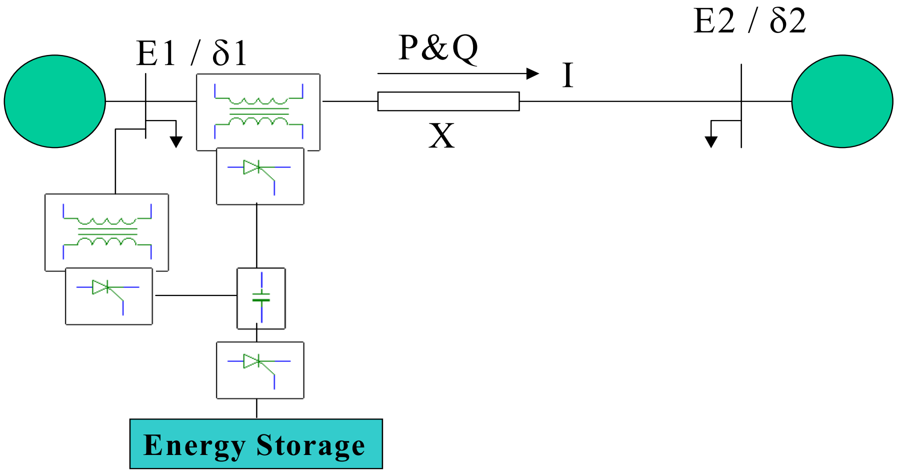


Fig. 2-1. Typical configuration of ESS integrated to FACTS [28] (P.F. Ribeiro)

A schematic diagram of the application of FACTS/ESS in the supply of energy as discussed above is depicted in Fig. 2-2. Power electronics are already integrated into networks on a large scale.

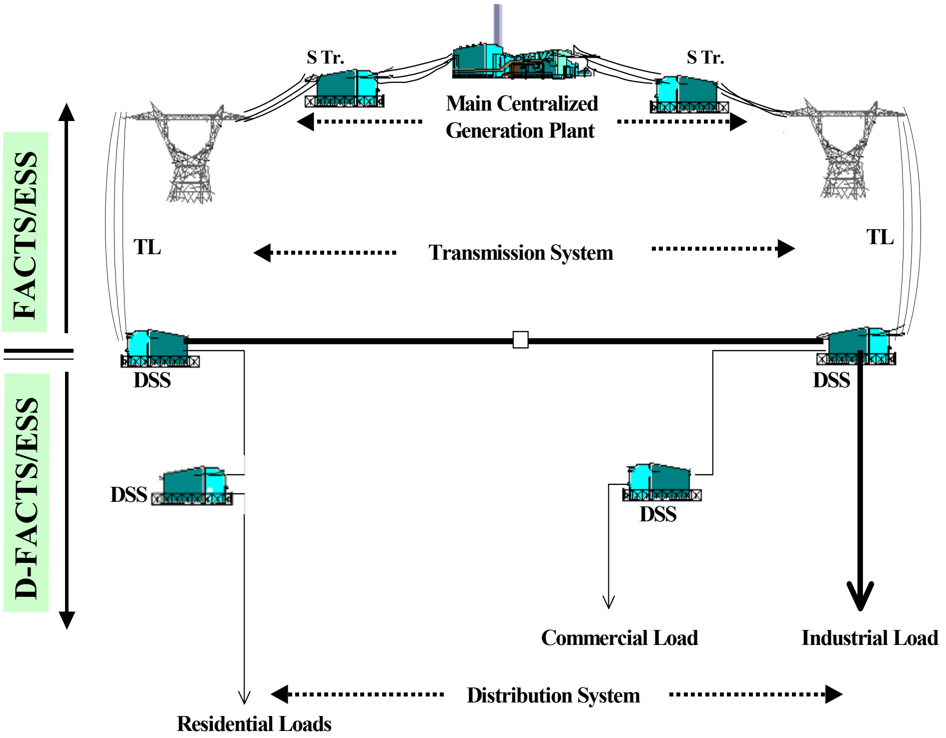


Fig. 2-2. Power electronic applications in supply of electric energy

2.2 General Principles of FACTS Devices

2.2.1 Basic Types of FACTS Power Controllers

In general, FACTS controllers can be divided into three categories [15]:

- Series Controllers,
- Shunt Controllers,
- Combined series-shunt Controllers.

Series Controllers: the series controller could be variable impedance, such as capacitor, reactor or a power electronics based variable voltage source at main frequency, sub-synchronous and harmonic frequencies (or combination) to serve the desired need. In principle, all series controllers inject a voltage in series with the line. Even variable impedance multiplied by the current flowing through it, represents an injected series voltage in the line. As long as the phase voltage is in quadrature with the line current, the series controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well [15].

Shunt Controllers: as in the case of the series controller, the shunt Controller may be a variable impedance (reactor or capacitor), variable source, or a combination of these. In principle, all shunt controllers inject a shunt current into the system at the point of connection. Even a variable shunt impedance connected to the line voltage causes a variable current flow and hence represents injection of shunt current into the line. As long as the injected phase current is in quadrature with the line voltage, the shunt controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well [15].

Combined series-shunt Controllers: this could be a combination of separate shunt and series controllers, which are controlled in a co-ordinated manner, or a *Unified Power Flow Controlle*r with series and shunt elements. In principle, combined shunt and series Controllers inject current to the system with the shunt part of the controller and voltage in series in the line with the series part of the controller. However, when the shunt and series controllers are unified, there can be a real power exchange between the series and shunt controllers via the DC power link [15].

The power system has only certain variables that can be impacted by control, which are:

- Voltage
- Angle
- Impedance

With the establishment of “what” variables can be controlled in a power system, followings are different types of FACTS devices that can control certain variables of power system, shown in Fig. 2-3.

- Static Synchronous Compensator (STATCOM)
    - Controls Voltage
- Static Var Compensator (SVC)

  - Controls Voltage
- Unified Power Flow Controller (UPFC)
- Convertible Static Compensator (CSC)
- Inter-phase Power Flow Controller (IPFC)
- Static Synchronous Series Controller (SSSC)
  - Each of the aforementioned (and similar) controllers impact voltage, impedance, and/or angle (and power))
- Thyristor Controlled Series Compensator (TCSC)
  - Controls Impedance
- Thyristor Controlled Phase Shifting Transformer (TCPST)
  - Controls angle
- Super Conducting Magnetic Energy Storage (SMES)
  - Controls voltage and power

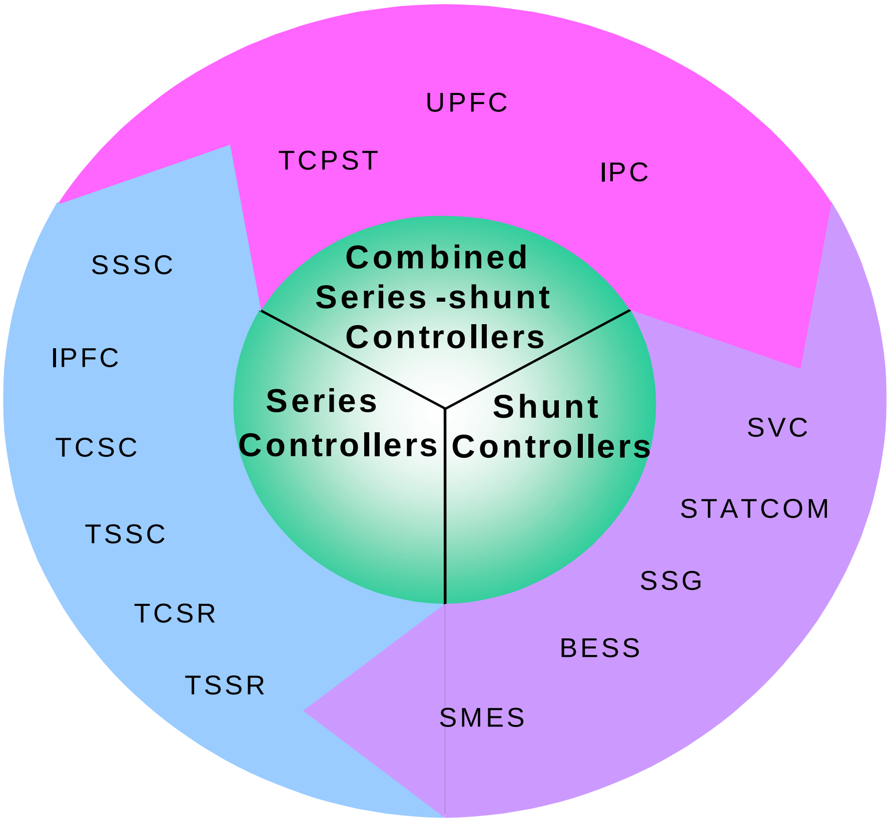


Fig. 2-3. The basic types of FACTS controllers

The FACTS Terms & Definitions Task Force of the FACTS Working Group of the DC and FACTS Subcommittee of IEEE made the definition of each above FACTS controllers in [33] as follows.

- **Static Synchronous Compensator (SSC or STATCOM)**: a static synchronous generator operated as a shunt-connected static var compensator whose capacitive of inductive output current can be controlled independent of the ac system voltage.

- **Static Var Compensator (SVC)**: A shunt-connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electric power system (typically bus voltage).

- **Unified Power Flow Controller (UPFC)**: a combination of a static synchronous compensator (STATCOM) an a static synchronous series compensator (SSSC) which are coupled via a common dc link, to allow bi-directional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM, and are controlled to provide concurrent real and reactive series line compensation without an external electric energy source. The UPFC, by means of angularly unconstrained series voltage injection, is able to control, concurrently or selectively, the transmission line voltage, impedance, and angle or, alternatively, the real and reactive power flow in the line. The UPFC may also provide independently controllable shunt reactive compensation.

- **Interphase Power Controller (IPC)**: a series-connected controller of active and reactive power consisting, in each phase, o inductive and capacitive branches subjected to separately phase-shifted voltages. The active and reactive power can be set independently by adjusting the phase shifts and/or the branch impedances, using mechanical or electronic switches. In the particular case where the inductive and capacitive impedances from a conjugate pair, each terminal of the IPC is a passive current source dependent on the voltage at the other terminal.

- **Static Synchronous Series Compensator (SSSC)**: a static, synchronous generator operated without an external electric energy source as a series compensator whose output voltage is in quadrature with, and controllable independently of, the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the line and thereby controlling the transmitted electric power. The SSSC may include transiently rated energy storage or energy absorbing devices to enhance the dynamic behavior of the power system by additional temporary real power compensation, to increase or decrease momentarily, the overall real (resistive) voltage drop across the line.

- **Thyristor Controlled Series Capacitor (TCSC)**: a capacitive reactance compensator which consists of a series capacitor bank shunted by thyristor controlled reactor in order to provide a smoothly variable series capacitive reactance.
- **Thyristor Controlled Phase Shifting Transformer (TCPST)**: a phase-shifting transformer, adjusted by thyristor switches to provide a rapidly variable phase angle.
- **Superconducting Magnetic Energy Storage (SMES)**: a superconducting electromagnetic energy storage device containing electronic converters that rapidly injects and/or absorbs real and/or reactive power or dynamically controls power flow in an ac system.

2.2.2 Typical Applications in Power Systems

The application of FACTS controllers in power system can obtain, on a case-by-case basis, one or more of the following benefits [33]. The contributions of each FACTS controller are shown in Table 2-1.

- Control of power flow
- Increase the loading capability of lines
- Improve transient stability limit during contingencies
- Reduce the short-circuit power level
- Compensate reactive power
- Improve dynamic voltage stability
- Control loop power flow
- Damp power oscillation
- Mitigate voltage unbalance due to single-phase loads

Table 2-1. Comparison of FACTS controller applications

FACTS Controller	**Voltage Control**	**VAR Compensation**	**Oscillation Damping**	**Stability Control**	**Power Flow Control**	**Short-circuit Limitation**	**Unbalance Compensation**
STATCOM	X	X	X	X			X
BESS/SMES	X	X	X	X			
SVC	X	X	X	X			X
TCSR			X	X			
SSSC			X	X	X	X	
TCSC			X	X	X	X	
IPFC	X	X	X	X	X	X	
UPFC	X	X	X	X			
TCPST			X	X	X		

2.3 General Principles of Energy Storage Systems

We see a growing interest in energy storage technologies for power quality compensation and utility power flow applications. With the increased utilization of large wind energy generation, the negative effects of pulsating power, voltage flicker and power imbalance make large-scale storage technologies interesting. Most of these storage options can easily be interfaced with voltage source converters. Storage technology options and energy density increase, while prices are reducing. Storage options for both power quality and FACTS applications are being interested in utilities [100].

2.3.1 Basic Types of Energy Storage Systems

Following is the general category of energy storage systems that are applied in electric power system.

- Battery energy storage system

- Superconducter energy storage system
- Super capacitor energy storage
- Flywheels
- Pumped hydro energy storage system
- Compressed air energy storage

Battery energy storage: Battery is popular for power quality, stability and some spinning reserve applications, as being one of the oldest and most developed energy storage technologies. Its short cycle life limits its application for energy management. Lead-acid batteries, nevertheless, have been used in a few commercial and large-scale energy management applications [34].

Superconductor energy storage system: There are three main parts of a SMES system, including a superconducting coil, the cryogenic system, and the power conversion with control and protection functions. Energy is stored in the magnetic field generated by circulating the DC current through a superconducting coil. The fundamental of superconductivity is that it is lack of resistance of conducting materials below certain temperature, which makes SMES with a fantastic potential applications in electric power system, including power system transmission control, stability control and power quality enhancement [34]

Super capacitor energy storage: The energy density and capacitance of electrochemical capacitors (EC) is thousands of times larger than the ordinary electrolytic capacitors, which stores electrical energy in the two series capacitors of the electric double layer (EDL). The electrodes are often made with porous carbon material, which is either aqueous or organic. EC capacitors have lower energy density but they can be cycled tens of thousands of times and are much more powerful than batteries (fast charge and discharge capability) by comparing with the other energy storage technologies [34].

Flywheels: In power system, the flywheel is connected to a motor/generator mounted onto the stator that, through some power electronics, interact with the utility grid. Reducing the drag is the key way to improve efficiency of the flywheel system, which is operated in a low vacuum environment. Most modern flywheel energy storage systems consist of a massive rotating cylinder (comprised of a rim attached to a shaft) that is substantially supported on a stator by magnetically levitated bearings that eliminate bearing wear and increase system life. Comparing with the other energy storage technologies, flywheels have the advantages like little maintenance, long life (20 years or 10s of thousands of deep cycles) and environmentally inert material. Flywheels can bridge the gap between short term ride-through and long term shortage with excellent cyclic and load following characteristics [34].

Pumped hydro energy storage: Historically, pumped hydro energy storage is the main energy storage system applied in power system. Conventional pumped hydro uses two water reservoirs, separated vertically. During off peak hours water is pumped from the lower reservoir to the upper reservoir. When required, the water flow is reserved to generate electricity. There are several types of pumped hydro energy storage like high dam hydro plants, underground pumped storage and open sea. Adjustable speed machines are now being used to improve efficiency in the pumped hydro energy storage system. Pumped hydro is available at almost any scale with discharge times ranging from several hours to a few days. Their efficiency is in the 70% to 85% range. There is over 90GW of pumped storage in operation world wide, which is about 3% of global generation capacity. Its main applications are for energy management, frequency control and provision of reserve. However, the long construction times and high capital expenditure are the shortcomings of this kind of energy storage technology [34].

Compressed air energy storage: In the compressed air energy storage system, the compressed air is often stored in appropriate underground mines or caverns inside salt rocks. Generally, this kind of energy storage system is a peaking gas turbine power plant consumes less than 40% of the gas used in conventional gas turbine to produce the same amount of electric output power. The shortage of this technology is the restrains of the geographical environment [34].

2.3.2. General Applications in Power System

According to the study conducted by Sandia National Laboratories, it is estimated that generation and transmission applications of energy storage technology could represent \$17.2B in national benefit in the United States [20]. The application of energy storage system has been identified in 10 groups that are shown in Fig. 2-4 in different categories. It is important to note that even though energy storage system can play unique role in a specific application situation or application type, however, those energy storage systems have proven most valuable when they perform multiple functions in more than one of the groups of applications. Followings are the definition of energy storage system application categories in power system [20].

- **Rapid Reserve**: generation capacity that a utility holds in reserve to meet National Energy Reliability Council (NERC) Policy 10 requirements to prevent interruption of service to customers in the event of a failure of an operating generating station.
- **Area Control and Frequency Responsive Reserve**: the ability for grid-connected utilities to prevent unplanned transfer of power between themselves and neighboring utilities (area control) and the ability of isolate utilities to instantaneously respond to frequency deviations (frequency responsive reserve). Both applications stem from NERC Policy 10 requirements.
- **Commodity Storage**: storage of inexpensive off-peak power for dispatch during relatively expensive on-peak hours.
- **Transmission System Stability**: ability to keep all components on a transmission line in synchronization with each other and prevent system collapse.
- **Transmission Voltage Regulation**: ability to maintain the voltages at the generation and load ends of a transmission line within 5 percent of each other.
- **Transmission Facility Deferral**: ability of a utility to postpone installation of new transmission liens and transformers by supplementing the existing facilities with another resource.
- **Distribution Facility Deferral**: ability of a utility to postpone installation of new distribution lines and transformers by supplementing the existing facilities with another resource.
- **Renewable Energy Management**: applications through which renewable power is available during peak utility demand (coincident peak) an available at a coincident level.
- **Customer Energy Management**: Dispatch of energy stored during off-peak or low-cost times to manage demand on utility sourced power.
- **Power Quality and Reliability**: ability to prevent voltage spikes, voltage sags, and

power outages that last for a few cycles (less than one second) to minutes from causing data and producing loss of customers with demands of less 1 MW.

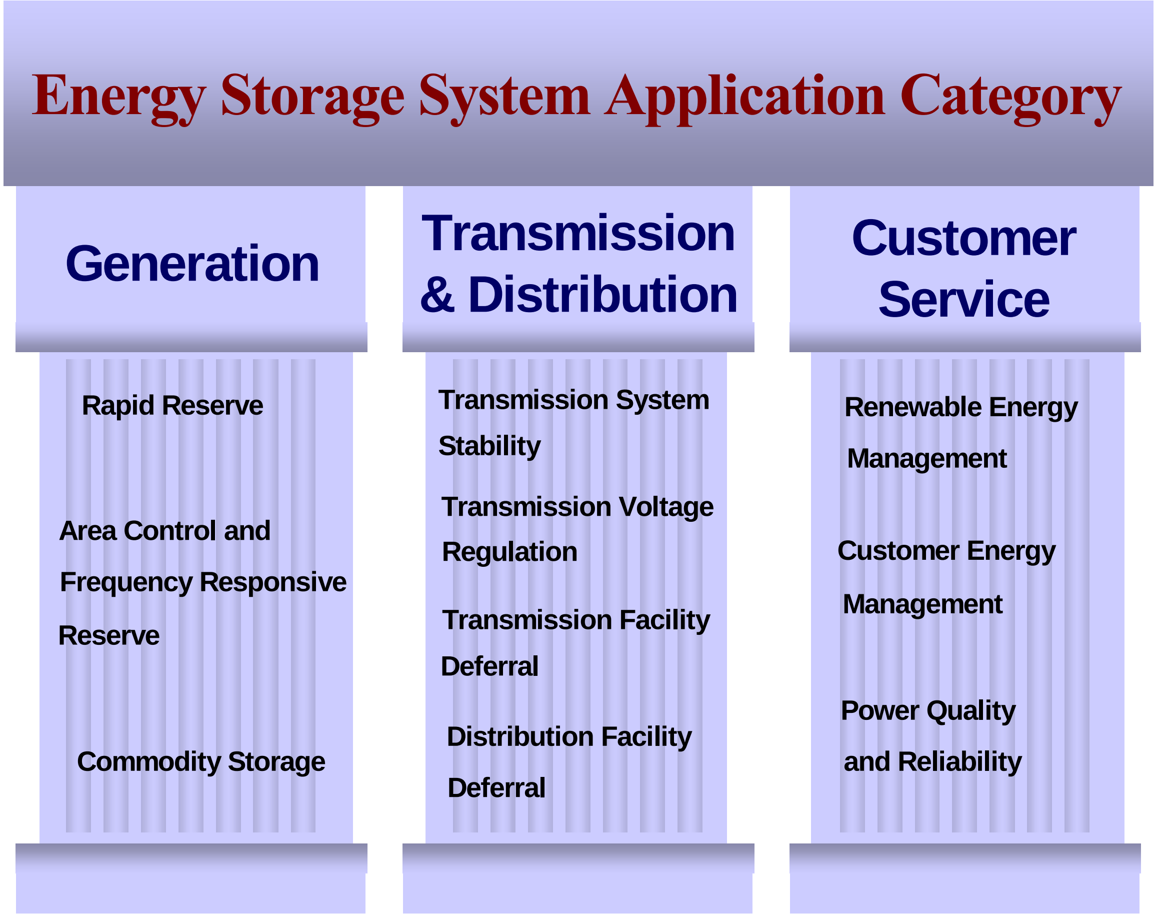


Fig. 2-4. The application category of energy storage system

Power quality applications of storage technologies normally require short storage durations with bridging times of seconds to minutes. The low speed flywheel is the best according to this requirement. The second one is the SMES operating at a lower power and lower energy content. Super-capacitor is the third based on this requirement. The battery is suitable for medium-term energy storage with a high-energy content and low discharge rate. However, a high-speed flywheel does not fit the requirement because it stores more energy, with charging and discharging power lowered by the high-speed electrical machine [30, 31, 100].

Even though SMES and super-capacitor have the characteristics of short ride through time and high investment costs, SMES is suitable for compensation of voltage dips and short interruptions (typical less than 2 seconds). Super-capacitor may suitable to UPS application if the cost will drop. The high-speed flywheel is in about the same cost range as the SMES and about 5 times more expensive than a low speed flywheel due to its more complicated design and limited power rating of the high-speed electrical machine. Low speed flywheels and battery storage systems have a high degree of maturation; have a simple design and a high degree of rationalisation. Below a storage time of 25 seconds the low speed flywheel becomes more cost effective than the battery [100].

For the maintenance aspect, Lead Acid battery needs much more maintenance than the other energy storage units. The maintenance of Lead Acid battery includes several different maintenance tests as visual, specific gravity, the levels of electrolyte and battery-testing system. The flywheel system only needs the bearings to be greased at a regular interval. For SMES device, only the "cold head" on the cryogenic unit needs regular replacement [110].

The frequency of charge and discharge cycles has an effect on the life span of the energy storage device. Flywheels and SMES devices can sustain an unlimited number of charge/discharge cycles because charge and discharge have no effect on their life span. Charge time of flywheels and SMES devices are shorter than the charge time of Lead-Acid batteries. Flywheels and SMES devices are therefore well suited for applications were the power quality mitigation is frequently needed. These devices can also supply all their energy in a short time (seconds) whereas Lead-Acid batteries are more suited for discharges over a longer period (>10 minutes) [105].

2.4 Summary

In bulk power system, the use of power electronics based devices can potentially overcome limitations of the present mechanically controlled transmission system. These flexible networks help delay or minimize the need to build more transmission lines and enable neighbouring utilities and regions to economically and reliably exchange power.

The potential benefits of FACTS equipment are now widely recognized by the power systems engineering and T&D communities. In the decentralized control of transmission systems, FACTS devices offer increased flexibility. As the vertically integrated utility structure is phased out, centralized control of the bulk power system will no longer be possible. Transmission providers will be forced to seek means of local control to address a number of potential problems such as uneven power flow through the system (loop flows), transient and dynamic instability, subsynchronous oscillations, and dynamic overvoltages and undervoltages.

Integrating an energy storage system (ESS), such as battery energy storage system (BESS), superconducting magnetic energy storage (SMES), flywheel energy storage, or supercacitor energy storage, into a voltage source converter (VSC)-based FACTS device can lead to improved controller flexibility by providing dynamic decentralized active power capabilities. Combined FACTS/ESS can improve power flow control, oscillation damping, and voltage control easily and economically. Considerable attention has been given to developing control strategies for a variety of VSC-based FACTS devices to mitigate a wide range of potential bulk power system problems [23, 31].

However, more and more efforts should be put into the application study of those equipments that can bring great benefits to bulk power system security and reliability.

Chapter 3. Power Quality Problems Solution by FACTS/ESS

3.1 Background

Because many of the electronic devices in common use today are extremely sensitive to the quality of the electric power, the quality of electric power available to the end user is a matter of increasing concern to the power systems engineer. Even though the electric power engineering has been devoted to the enhancement of the quality of the power supply since the beginning of the use of electricity, a wide variety of microelectronic devices in the electric power system today suffer the unsatisfied power quality, which induced even the failure of those electronics devices. Power quality becomes one a critical issue both to utility and the consumers. More efforts from both side has been taken into the study of power quality enhancement [53, 54].

Generally, good power quality means that the system supplies and maintains load voltage as a pure, sinusoidal waveform at specified frequency and voltage to all the power consumers in the power system, although power quality means different things to different people. The possible causes of power quality problems can generally be classified into one of the following phenomena, which is shown in Fig. 3-1 [53, 54].

- Voltage sag
- Overvoltage
- Momentary interruption
- Transient
- Harmonic distortion
- Electrical noise

Flicker is another power quality problem that affects our daily lives, which is defined as the "impression of fluctuating brightness or color, occurring when the frequency of observed variation lies between a few hertz and the fusion frequency of images." The frequency range of voltage flicker is between 1 Hz and 10 Hz. Flicker was always considered a power quality problem for only incandescent lamps, but the phenomenon is now becoming noticeable due to the increasing system pollution with interharmonics, even the pollution of fluctuations to the vicinity generators in the same distribution system. When the voltage magnitude varies due to fast load changes, power flow to the equipment will normally vary, which may cause stability problem in the system. The harmful thing is, if the variation is large enough or is within a certain critical frequency range, the equipment performance can be affected, like motors, electronic devices, and process controllers. The primary generators of voltage fluctuation are arc furnaces, welders, alternators, and motors [53, 54].

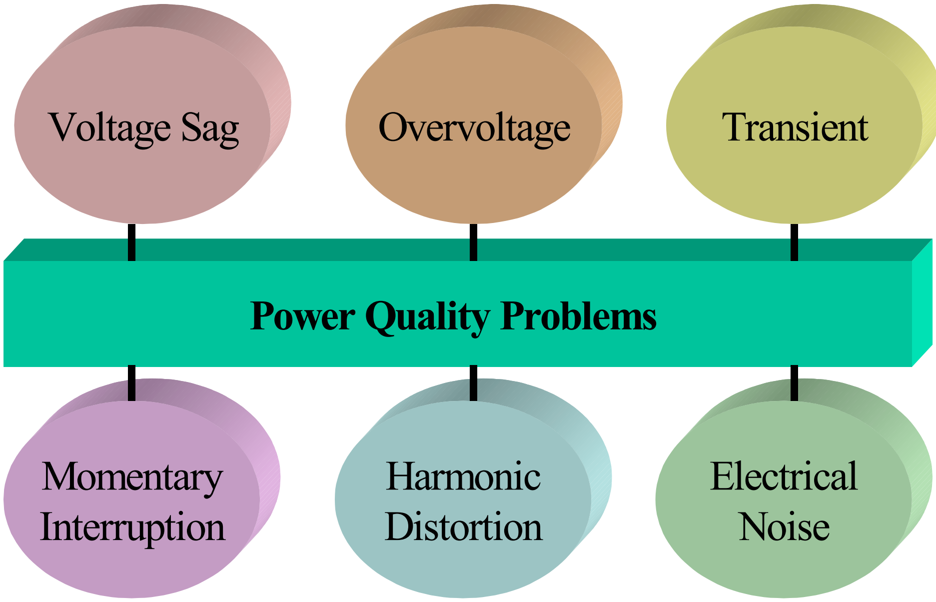


Fig. 3-1. Power quality problems

Voltage fluctuation is a voltage regulation issue, which is a major problem in the electric power industry. The concept of voltage fluctuation involves voltage magnitude and frequency of occurrence. Because of the competitive cost of producing steel with such furnaces and easily air pollution control, steel companies are building more large-capacity arc furnaces, which are considered as desirable loads due to the large amount of power required and the high power factor (between 75% and 90%) even though arc furnaces cause numerous problems to the utility [54].

A utility's main concern is usually the restriction placed upon an individual industry due to the effect upon other customers. Some utilities are concerned with whether unacceptable voltage fluctuations in a system with result in complaints from customers actually experiencing light flicker. The principal source of voltage fluctuation leading to flicker is the electric arc furnace [54].

Due to the load concept that any change in the lamp intensity is a “light flicker”, sometimes the term voltage fluctuation is erroneously used as voltage sag. Technically, voltage sag is defined as a reduction in the rms magnitude of the voltage from 10 to 90% with a duration form 0.5 cycle to 1 minute [41]. On the other hand, noncyclic flicker is defined as that corresponding to occasional voltage fluctuations (less frequently than once per hour) such as that caused by the starting of a motor, a phenomenon considered today as voltage sag [42]. The repetitive character and voltage change magnitude are the principal differences between the two phenomena, as “voltage sag” and “voltage flicker” [54].

Being considered as minor variations in electric power, voltage fluctuation and voltage flicker were generally ignored by the conventional electric equipment. The negative effects were not obvious in the traditional power system. Nowadays, the sophisticated, high performance computers, controllers and other electronic equipment of today operate on such short time scales that it simply cannot tolerate disturbances that were once considered to be minor. The loss of valuable computer data, reset of a programmable controller in a factory, or even the complete shutdown of a factory is not endurable.

Disturbance, even though short in duration, can be extremely expensive. For example, it has been estimated that at a single plant, a five cycles interruption (an outage of less than a tenth of a second) can cost about $200,000. Other major manufacturers indicate that an outage of two seconds can cost as much as $600,000. In addition, the performance of most assembly line equipment is sensitive to voltage level, transients and harmonic content [53].

The source of power quality problems may originate in the following parts of electric power system shown in Fig. 3-2 [53].

- Generators and associated equipment
- Transmission lines and associated equipment

- Distribution subsystem
- Loads

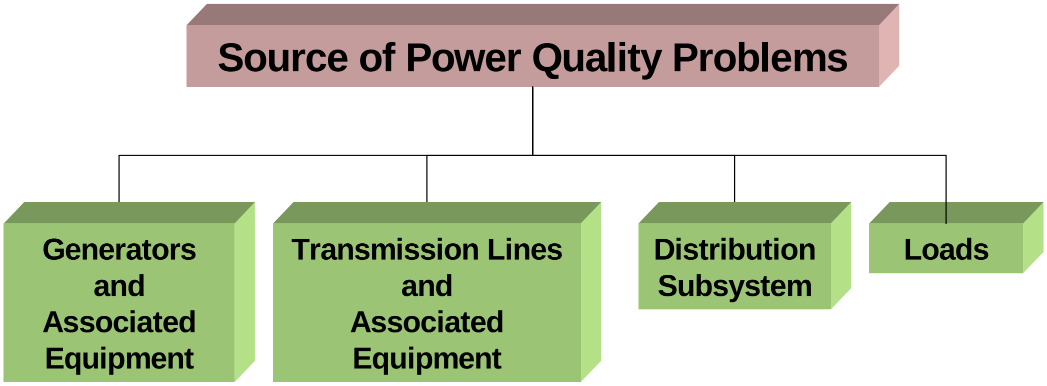


Fig. 3-2. Sources of power quality problems

Regardless of the location of the problem, the possible source can usually be attributed to one of the following [53].

- Lightning strike
- System fault
- Switching of large loads
- Breaker operation
- Utility switching
- Nonlinear loads
- Ferroresonance
- Semiconductor switching devices
- Improper grounding

Arc furnaces are being used in greater numbers and at ever increasing ratings. They are currently an important part of the process in the production of steel and other materials. Two types of arcs are typically utilized namely dc arcs or ac arcs. DC arc furnaces have been typically confined to applications at lower power levels. This limitation arises as a result of constraints imposed by the cost of the AC to DC converter and the design of the bottom electrode. The above concerns can be addressed by considering an ac arc furnace especially at increasing power levels [55, 56].

The operation phrases of the arc furnace include bore-down, meltdown, and refining. Also, the general operation behavior of the arc furnace is known to be stochastic [41- 45]. To cope with the voltage flicker problem, many utilities/organizations attempt to:

- Establish quantifiable flicker limits
- Develop instrument measurement
- Compensate for the flicker phenomenon
- Develop predictive technology for adding new arc furnace loads.

As we know, X/R ratio is very important when we study the effect of active and reactive load, which is consumed by EAF, on the voltage and angle fluctuation in the system [51]. The voltage effect of active power is reflected by the real part of system impedance (Thevenin Impedance) R_{th}. A very common mistake is to assume that in the power system, the X/R ratio is large enough to omit the voltage drop caused by the active power. An incorrect approach to calculating X/R ratio is by considering only the upper transformer or branch. Using this approach one will certainly arrive at an X/R of over 10. The correct approach is by looking at all of the parameters including the load. In other words, the R and X are not proportional to the impedance of the upper transformers and lines; instead they should be the Thevenin Impedance seen from the PCC bus of the entire system.

The study in this chapter is based on a real project supported by Tennessee Valley Authority (TVA), which tried to solve real power quality problems induced by electric arc furnace in TVA power system. A 40 MVA arc furnace is located at Hoaganaes in TVA system, which causes severe power quality problems to the nearby system, especially to the generators in the vicinity system. From the year 2003, the power engineering group in ECE department at Virginia Tech conducted a project to propose proper solutions to these problems. This study includes the impact of EAF operation study and mitigation study.

3.2 Impact of Active and Reactive Load

In this section, the focus is the study of impact of different kinds of load on the operation and dynamics of power system. The author uses 30MW pulsing active load and 30MVAR pulsing reactive load to make the comparison. The operation of the load is the periodic drawn of power (active or reactive) from power system. The frequency of this periodic draw of power is 5 Hz.

The general scheme of active load and reactive load connecting to system is shown in Fig. 3-3.

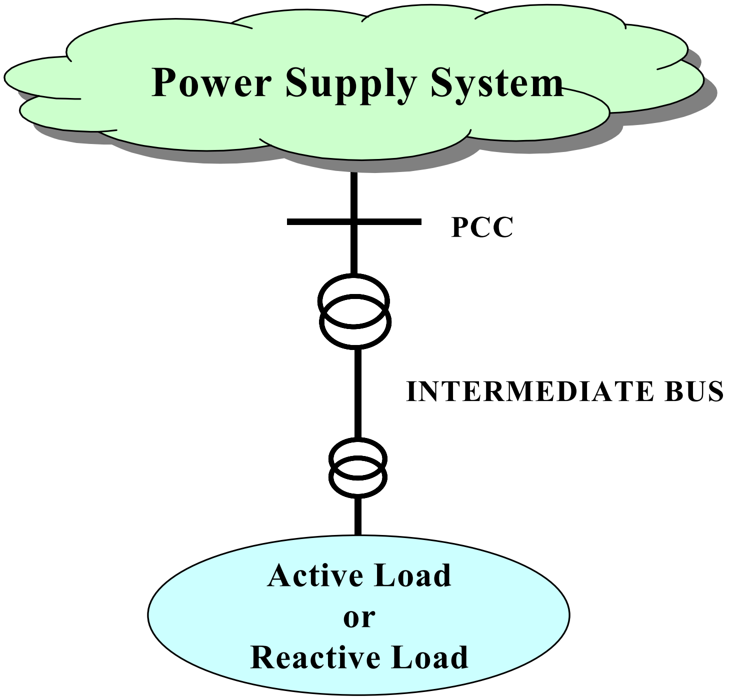


Fig. 3-3. The general scheme load and compensator

In this study, the Eastern U.S. system that contains the major portion of the NERC (North American Electric Reliability Council) is used. The simulated system is comprehensive, containing high voltage level 765kV transmission circuits and lower voltage distribution circuits. The focus of this study is to find out the impact of pulsing active load and reactive load on the generators in the nearby system. Fig. 3-4 is the detail of the subject system structure.

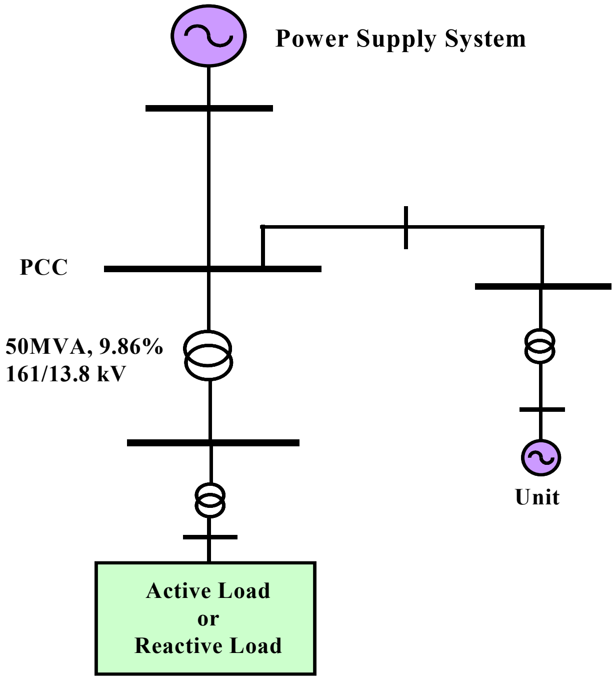


Fig. 3-4. One-line diagram of the subject system

Fig. 3-5 shows the periodic change of 30MW pulsing active load or 30MVAR pulsing reactive load. Fig. 3-6 shows the PCC bus voltage magnitude fluctuation by the periodic active load or reactive load. The voltage drop by the 30MVAR reactive load is about 3 times of that caused by 30MW active load.

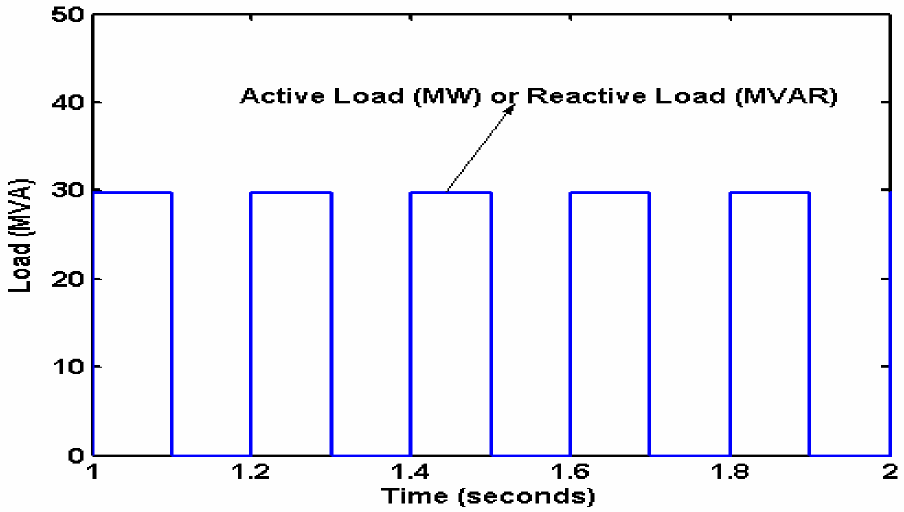


Fig. 3-5. The rapid change power drawn by 30MW or 30 MVAR loads

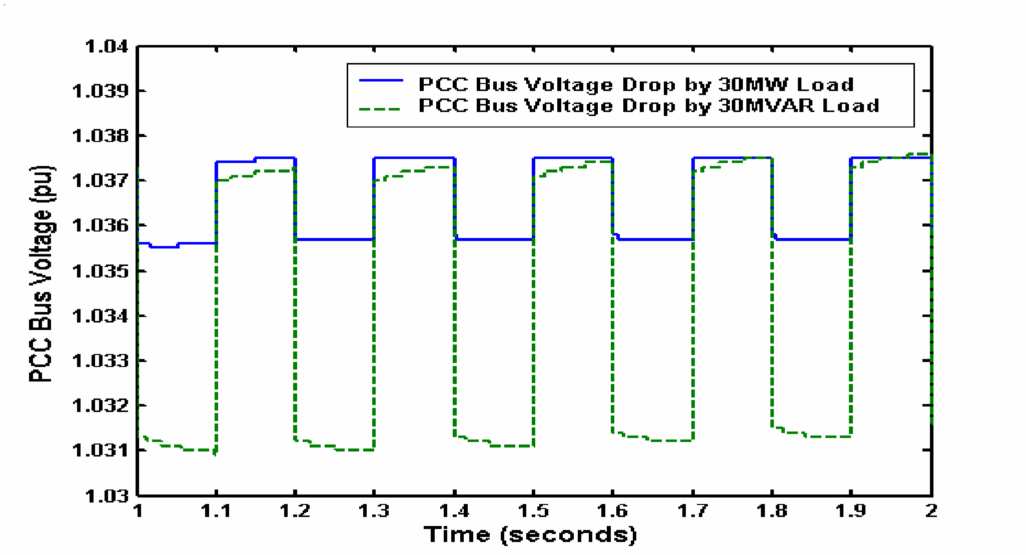


Fig. 3-6. PCC bus voltage drop by 30MW load or 30MVAR load

Fig. 3-7 shows the PCC bus angle fluctuation by different kinds of load. 30MW active load brings much more bus angle fluctuation than that by 30MVAR reactive load. The bus angle fluctuation caused by active load has the opposite phase of that caused by the reactive load. For the generators in the nearby system, the generator angle oscillates because of the pulsing active load and reactive load.

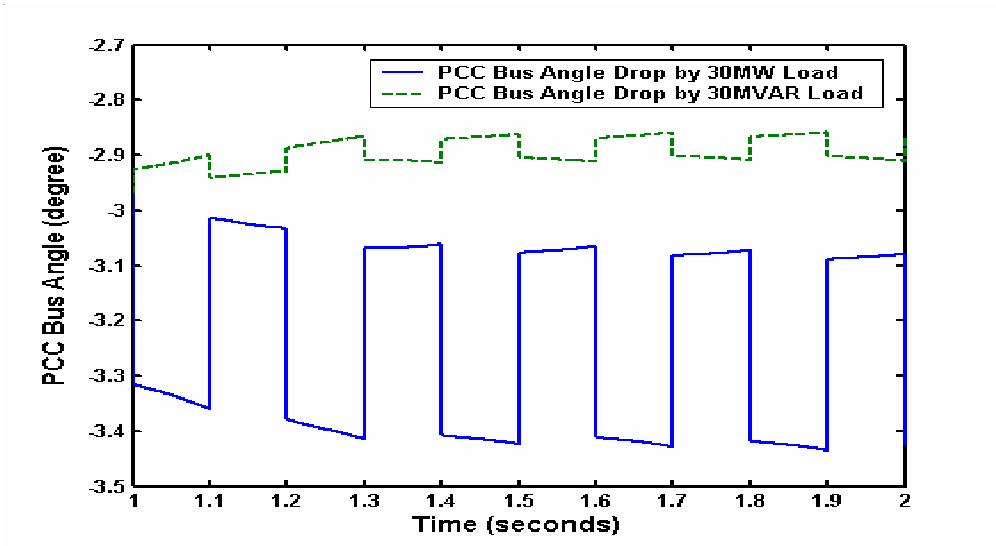


Fig. 3-7. PCC bus angle oscillation caused by 30MW load or 30MVAR load

In Fig. 3-8, the generator angle oscillation caused by 30MW active load is larger than that by the same amount of reactive load. The angle oscillation caused by the tow different kinds of load also shows the opposite phase phenomenon as that in Fig. 3-7. Fig. 3-9 shows that 30MW active load can cause more generator output active power fluctuation than that by the 30MVAR reactive load. On the contrary, the 30MVAR reactive load causes more generator reactive power output oscillation than that by the same value of active load as shown in Fig. 3-10.

From Fig. 3-6 to Fig. 3-10, we can see that the impact of active load and reactive load on power quality is quite different. Thus the compensation methods for the power quality problems caused by different kinds load should be different.

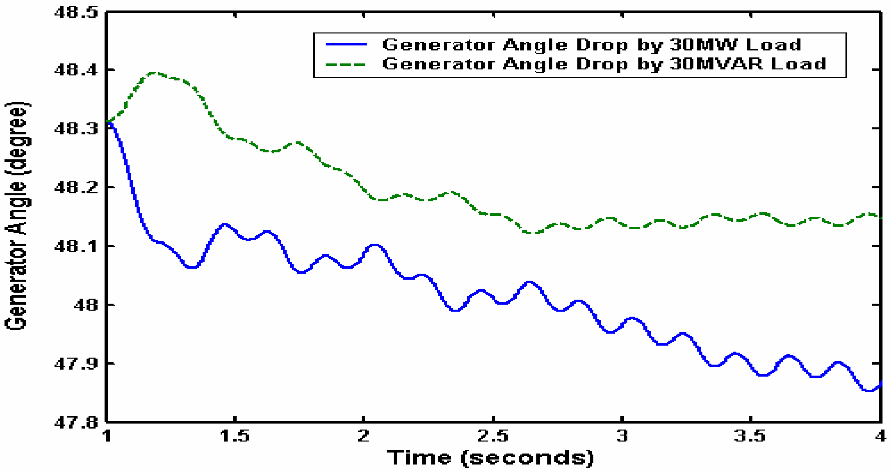


Fig. 3-8. Generator angle dynamics by 30MW load or 30MVAR load

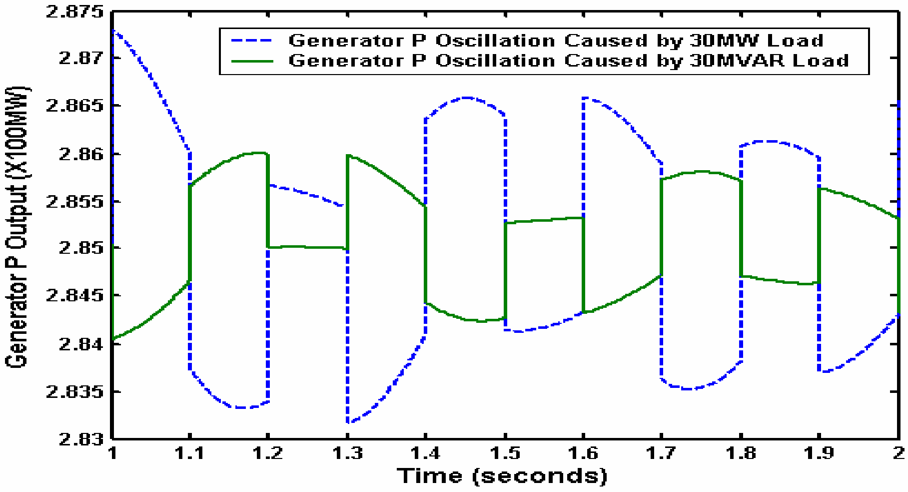


Fig. 3-9. Generator active power output oscillation caused by 30MW load or 30MVAR load

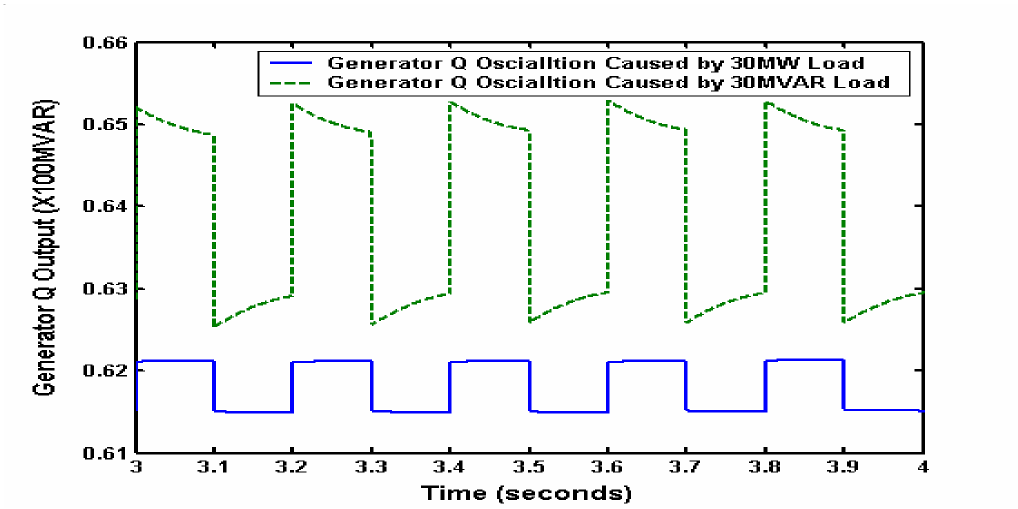


Fig. 3-10. Generator reactive power output oscillation caused by 30MW load or 30MVAR load

Active load can cause severe power quality problems associate with angle and active power flow. Reactive load can bring more severe problems associated with voltage and reactive power flow.

Following is an analysis of the above phenomena. As we know, the generator stator voltage equation is as follows:

$$\begin{cases} u_a = p\psi_a - r_a i_a \\ u_b = p\psi_b - r_a i_b \\ u_c = p\psi_b - r_a i_c \end{cases} \tag{3-1}$$

where r_f, r_D and r_Q is the resistance of the f, D and Q coil, respectively.

The rotor voltage equation of generator is as follows:

$$\begin{cases} u_f = p\psi_f + r_f i_f \\ u_D = p\psi_D + r_D i_D \equiv 0 \\ u_Q = p\psi_Q + r_Q i_Q \equiv 0 \end{cases} \tag{3-2}$$

where r_f, r_D and r_Q is the resistance of the f, D and Q coil, respectively.

Combining equations (3-1) and (3-2), we get the following vector equation:

$$\mathbf{u} = \mathbf{p\psi} + \mathbf{r} \bullet \mathbf{i} \tag{3-3}$$

where,

$$\mathbf{u} = (u_a, u_b, u_c, u_f, u_D, u_Q)^T$$
$$\boldsymbol{\psi} = (\psi_a, \psi_b, \psi_c, \psi_f, \psi_D, \psi_Q)^T$$
$$\mathrm{r} = diag\ (r_a, r_a, r_a, r_f, r_D, r_Q)$$
$$\mathrm{i} = (-i_a, -i_b, -i_c, i_f, i_D, i_Q)^T$$

The instant output active power of generator is as follows:

$$P_e = u_a i_a + u_b i_b + u_c i_c \tag{3-4}$$

The magnetic-electric torque is as follows:

$$\begin{aligned} T_e &= p_p \frac{1}{\sqrt{3}}[\psi_a(i_b - i_c) + \psi_b(i_c - i_a) + \psi_c(i_a - i_b)] \\ &= p_p \frac{1}{\sqrt{3}}\, \Psi_{abc}^T \begin{bmatrix} 0 & 1 & -1 \\ -1 & 0 & 1 \\ 1 & -1 & 0 \end{bmatrix} \mathrm{i}_{abc} \end{aligned} \tag{3-5}$$

where pp is the pole pairs of generator.

The generator rotor motion equation is as follows:

$$\begin{cases} J\dfrac{d^2\theta_m}{dt^2} = M_m - M_e \\ \dfrac{d\theta_m}{dt} = \omega_m \end{cases} \tag{3-6}$$

The operation of the periodic active and reactive load can cause not only the voltage and angle fluctuation of the PCC bus, but also the voltage and angle fluctuation on other feeders connected to the PCC bus, including the feeders of generators in the nearby system. From equation (3-1), (3-2) and (3-3) we know that the voltage U_{abc} change can cause the change of current i_{abc}. The fluctuation of U_{abc} and i_{abc} will bring the generator output active power fluctuation according to equation (3-4). The i_{abc} change will cause the change of torque T_e with the same trend. Because the input mechanical power (or torque) of the generator cannot change within such a short period of time, the swing of T_e finally causes the generator angle fluctuation with the same frequency.

In a multi-machine system, the output active and reactive power of the generator is as shown in equation set (3-7).

$$\begin{cases} P_{ei} = E_i^2 G_{ii} + \sum\limits_{\substack{j=1 \\ j\neq i}}^{n} (E_i E_j B_{ij} \sin\delta_{ij} + E_i E_j G_{ij} \cos\delta_{ij} \\ Q_{ei} = -E_i^2 B_{ii} + \sum\limits_{\substack{j=1 \\ j\neq i}}^{n} (E_i E_j G_{ij} \sin\delta_{ij} - E_i E_j B_{ij} \cos\delta_{ij}) \end{cases} \tag{3-7}$$

The fluctuation of generator angles will cause the fluctuation of active and reactive power output of every generator. The power flow of the system changes because of this fluctuation, which means the power distribution of the entire system will change. That may create serious stability problems in the bulk power system, especially with the critical bus and generators. That is very harmful to the generator shaft as well.

3.3 X/R Ratio Discussion

As we know, X/R ratio is very important when we study the effect of active and reactive load on the voltage and angle fluctuation in the system [51]. The voltage effect of active power is reflected by the real part of system impedance (Thevenin Impedance) R_{th}. A very common mistake is to assume that in the power system, the X/R ratio is large enough to omit the voltage drop caused by the active power. An incorrect approach to calculating X/R ratio is by considering only the upper transformer or branch. Using this approach one will certainly arrive at an X/R of over 10. The correct approach is by looking at all of the parameters including the load. In other words, the R and X are not proportional to the impedance of the upper transformers and lines; instead they should be the Thevenin Impedance seen from the PCC bus of the entire system as shown in Fig. 3-11. At the PCC bus, the whole power system can be seen as a power source connected with an active load and a reactive load as shown in Fig. 3-11(a). The Thevenin Equivalent circuit is shown in Fig. 3-11(b). Table 3-1 is the line or transformer impedance and X/R ratio in a 24-buses PTI sample system shown in Fig. 3-12. We show the terminal buses of each line or transformer, including the voltage level. The resistance and reactance of each bus or transformer are shown in the table as well. X/R ration is calculated by the value of resistance and reactance. From this table, we can see that the original X/R ratios of the transmission lines or transformers are higher than 8.

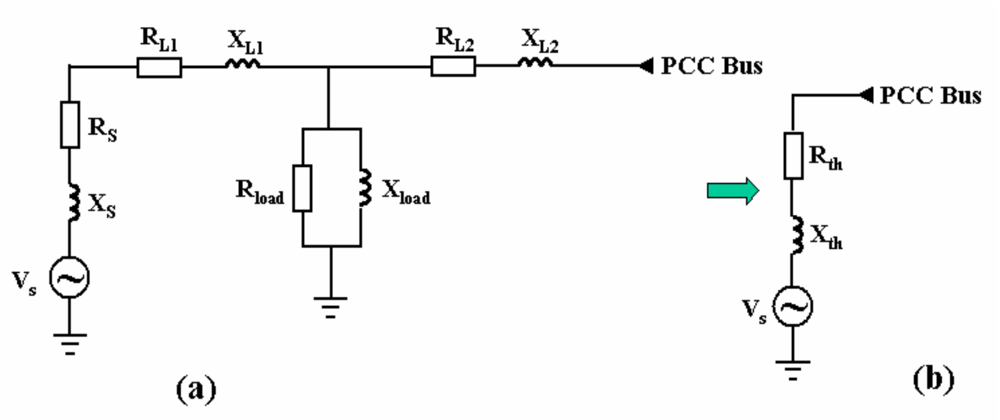


Fig. 3-11. Thevenin equivalent circuit of the whole system seen at PCC bus

We will use data in the following 24 buses sample system to roughly explain the X/R ratio calculation method in power system. This is a sample system provided by PTI, shown in Fig. 3-12. In original system, there are 23 buses. We add a new bus 1531 connecting the 30 MW active load or 30 MVAR reactive load to conduct the study. Six generators are included in this system. The total generation is 3258MW+j964MVAR, and the total load is 3200MW+j1950MVAR.

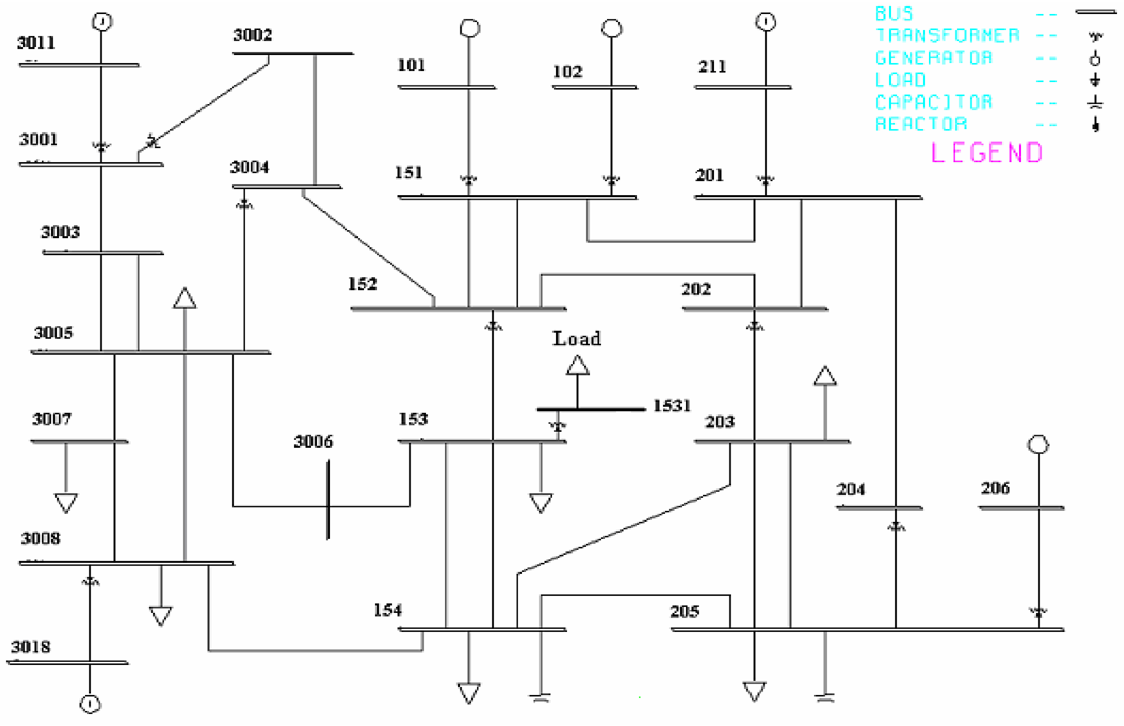


Fig. 3-12. One-line diagram of a 24 buses sample system

Table 3-1. X/R ratio of lines or transformers in the sample system

From Bus - To Bus	Equipment Type	Voltage Level (kV)	R (pu)	X (pu)	X/R Ratio
101-151	transformer	21.6-500	0.0003	0.0136	45.3
102-151	transformer	21.6-500	0.0003	0.0136	45.3
151-152	line	500	0.0026	0.046	17.7
151-152	line	500	0.0026	0.046	17.7
151-201	line	500	0.001	0.015	15
152-202	line	500	0.0008	0.01	12.5
152-3004	line	500	0.003	0.03	10
153-154	line	230	0.005	0.045	9
153-154	line	230	0.006	0.054	9
153-3006	line	230	0.001	0.012	12
154-203	line	230	0.004	0.04	10
154-205	line	230	0.0003	0.00333	10.1
154-3008	line	230	0.0027	0.022	8.1
201-202	line	500	0.002	0.025	12.5
201-204	line	500	0.003	0.03	10
201-211	transformer	500-20	0.0007	0.02125	30.3
202-203	transformer	500-230	0.0004	0.01625	40
203-205	line	230	0.005	0.045	9
203-205	line	230	0.005	0.045	9
204-205	transformer	500-230	0.0003	0.015	50
205-206	transformer	230-18	0.00026	0.01333	51.2
3001-3002	transformer	230-500	0.0003	0.015	50
3001-3011	transformer	230-13.8	0.0002	0.01	50
3002-3004	line	500	0.006	0.054	9
3003-3005	line	230	0.006	0.054	9
3003-3005	line	230	0.006	0.054	9
3004-3005	transformer	500-230	0.0004	0.01625	40.6
3005-3006	line	230	0.0035	0.03	8.6
3005-3007	line	230	0.003	0.025	8.3
3005-3008	line	230	0.006	0.05	8.3
3007-3008	line	230	0.003	0.025	8.3
3008-3018	transformer	230-13.8	0.00021	0.085	404.7

We use the generator at bus 101 data and the typical transmission line data in Fig. 3-12 as an example. We assume the output active power of this generator is 900MW (the active power output of generator at 101 bus), the total load P_{Load} is 810MW (90% of active generation of generator at bus 101) and Q_{Load} is 243MVAR (30% of P_{Load}). V_{LLbase} is 21.6kV and S_{base} is 100MVA. The impedance of the generator is $Z_s = 0.01+j0.3$. The impedance of the transmission line is $Z_{L1} = Z_{L2} = 0.003+j0.03$ pu.

$$Z_{base} = \frac{V_{LLbase}^2}{S_{base}} = 4.666\,\Omega \tag{3-8}$$

$$\begin{cases} R_{Load} = \dfrac{V_{LLbase}^2}{P_L} = 0.576\,\Omega = 0.123\ pu \\ X_{Load} = \dfrac{V_{LLbase}^2}{Q_L} = 1.92\,\Omega = 0.412\ pu \end{cases} \tag{3-9}$$

As shown in Fig. 3-11, we can compute the $R_{th}+jX_{th}=0.089+j0.085$, and $X_{th}/R_{th} \approx 1$. In this example, the values of X_{th} and R_{th} are not precise but enough to demonstrate that the system X/R ratio is affected significantly by the load. After adding impedances of adjacent transformer and line, X/R is still not large enough to omit R impact. In the sample system in Fig. 3-12, the system Thevenin Impedance ($R_{th}+jX_{th}$) seen at PCC bus (bus 153) is 0.00782 +j0.02389 pu, which was calculated precisely by PSS/E (PSS/E has the function of Thevenin Impedance calculation.). The X_{th}/R_{th} ratio is about 3. In this case, the active load can cause obvious voltage drop as seen in simulation results. Because it is difficult to calculate the precise Thevenin equivalent circuit for a particular bus in a power system with 10808 buses, we use a practical, called simulation method to estimate the draft Thevenin equivalent R_n, X_n, and X_n/R_n ratio in Fig. 3-13. In Fig. 3-13, the voltage drop ΔU caused by the active and reactive load, for example, is analyzed as follows in equations (3-10) through (3-13):

$$\Delta U = \frac{\sqrt{3}}{3} I_n * X_n (\sin\varphi + \frac{R_n}{X_n} * \cos\varphi) \tag{3-10}$$

$$\begin{cases} \Delta U_p = \dfrac{\sqrt{3}}{3} I_{np} * R_n \\ \Delta U_q = \dfrac{\sqrt{3}}{3} I_{nq} * X_n \end{cases} \tag{3-11}$$

$$\begin{cases} I_{np} = I_n \cos\varphi \\ I_{nq} = I_n \sin\varphi \end{cases} \tag{3-12}$$

$$\frac{\Delta U_p}{\Delta U_q} = \frac{I_{np}}{I_{nq}} * \frac{R_n}{X_n} = \frac{R_n}{X_n} * (\tan\varphi)^{-1} \tag{3-13}$$

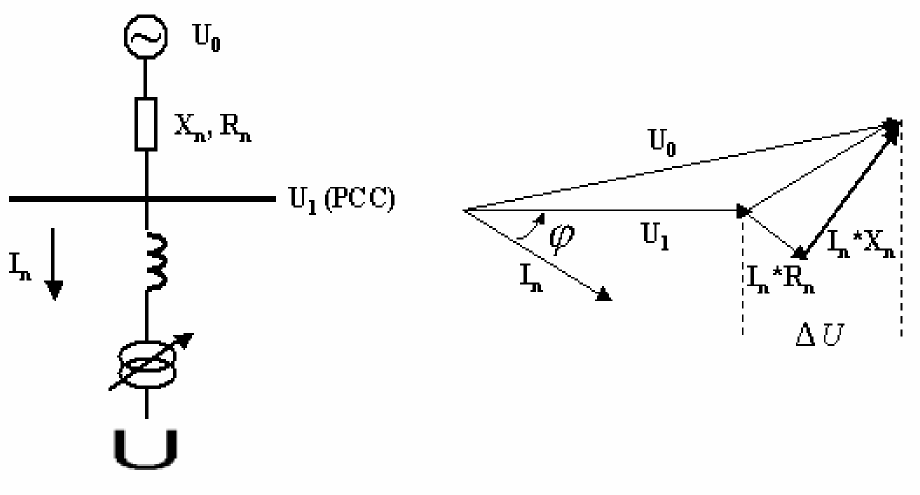


Fig. 3-13. X/R ratio discussion

In Fig. 3-6 and Fig. 3-14, we can check the ratio of voltage drop caused by 30MW active load and 30MVAR reactive load is about 0.295 in the real system. We can calculate the X/R ratio is about 3. One important application of this dynamic simulation X/R ratio calculation method is for the filed test, by which X/R ratio of certain bus in the power system can be identified by test without the system data file information.

In this study, we also use the above methodology to calculate the X/R ratio of each bus in this PTI sample system. PSS/E has the function to calculate the impedance and X/R ratio of each bus. We calculate X/R ratio of each bus in this PTI 23 bus sample system by both PSS/E and dynamic simulation methods. The result is shown in Table 3-2, which show that the X/R ratio of buses in the real power system is not the way which we think larger than 8 generally. The results show that the X/R ratio calculated by this dynamic simulation method is comparable to the PSS/E X/R ratio calculation function. The real X/R ratio of each bus in the system is about 3 for many cases.

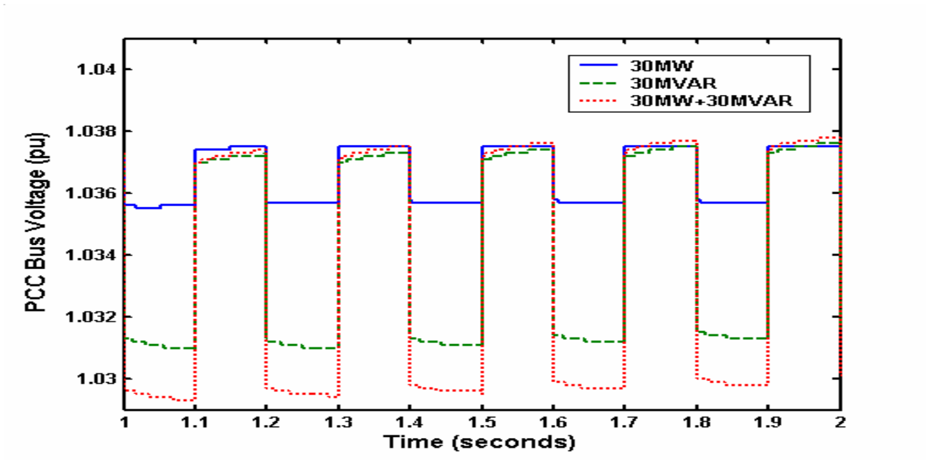


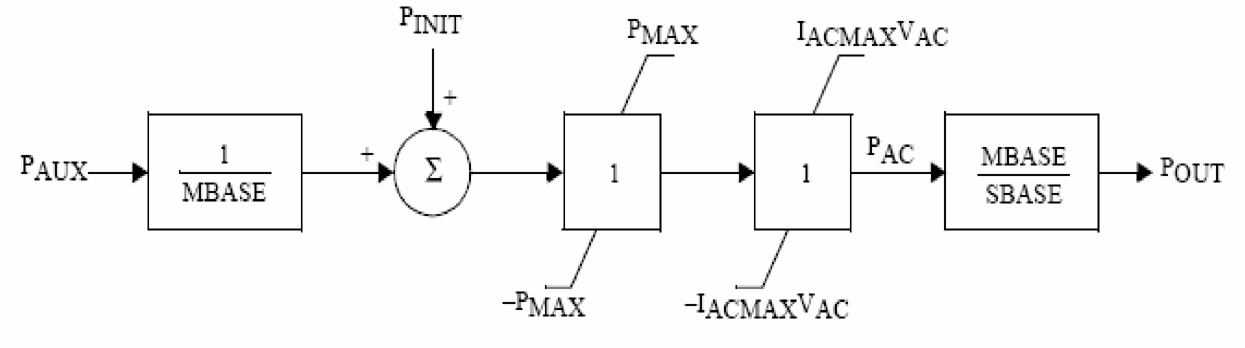
Fig. 3-14. Comparison of PCC bus voltage drop by active load (30MW), reactive load (30MVAR) and their combination (30MW+j30MVAR)

Table 3-2. Comparison of X/R calculated by PSS/E function and dynamic simulation

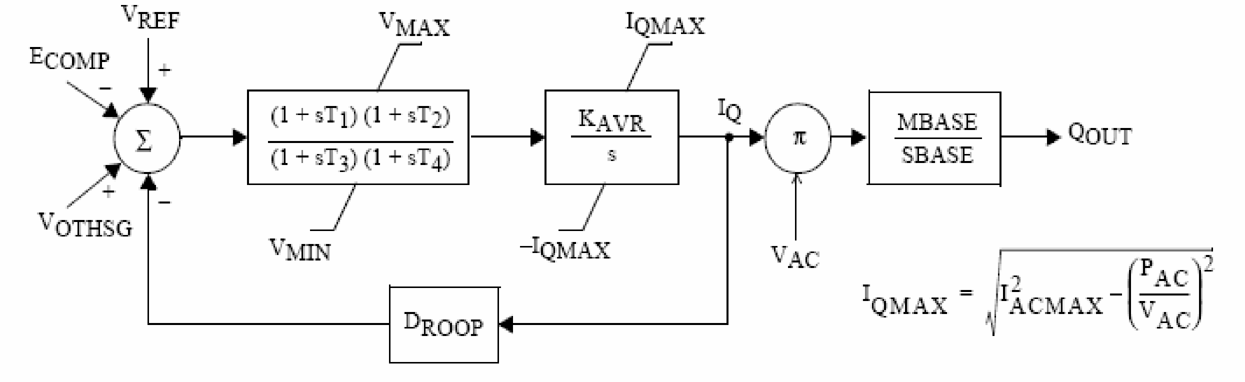
BUS	NAME	BASE KV	Using PSS/E Function			Using Dynamic Simulation
			THEVENIN IMPEDANCES		X/R	X/R
101	NUC-A	21.6	0.00304	0.02347	7.720	Gen. Bus
102	NUC-B	21.6	0.00304	0.02347	7.720	Gen. Bus
151	NUCPANT	500	0.00409	0.01765	4.315	7.56
152	MID500	500	0.00756	0.01887	2.496	2.62
153	MID230	230	0.00797	0.01928	2.419	2.39
154	DOWNTN	230	0.00914	0.01444	1.580	1.57
201	HYDRO	500	0.00549	0.0194	3.534	4.24
202	EAST500	500	0.0077	0.02011	2.612	2.67
203	EAST230	230	0.00931	0.02058	2.211	2.00
204	SUB500	500	0.00802	0.02299	2.867	2.69
205	SUB230	230	0.00882	0.01414	1.603	1.63
206	URBGEN	18	0.00571	0.01934	3.387	Gen. Bus
211	HYDRO_G	20	0.00329	0.02546	7.739	Gen. Bus
3001	MINE	230	0.00581	0.03174	5.463	5.40
3002	E.MINE	500	0.00673	0.03855	5.728	5.45
3003	S.MINE	230	0.00661	0.03258	4.929	4.85
3004	WEST	500	0.00818	0.02757	3.370	3.13
3005	WEST	230	0.00844	0.02371	2.809	2.71
3006	UPTOWN	230	0.00857	0.02593	3.026	2.88
3007	RURAL	230	0.01135	0.03115	2.744	2.51
3008	CATDOG	230	0.01024	0.02416	2.359	2.20
3011	MINE_G	13.8	0.00458	0.03305	7.216	Gen. Bus
3018	CATDOG_G	13.8	0.008	0.09141	11.426	Gen. Bus

3.4 Theory of Active Power Compensation

The PSS/E CBEST (EPRI Battery Energy Storage) model is used as the active power and reactive power compensator in this section shown in Fig. 3-15 [66]. In this study, we assume the active power compensator has enough active power storage during the control without the need to absorb active power from the power system for the future use. For the pure active function control, we block the reactive power output of this CBEST model to let the whole equipment behave like a pure active power compensator.



(a) Active power control



(b) Reactive power control

Fig. 3-15. The configuration of CBEST model [66]

The active power output of the compensator is shown in Fig. 3-16. The active power output is controlled in the way that the active power will keep as 30MW when the 30MW active load or the 30MVAR reactive load is on. Fig. 3-17 is the one-line diagram in the vicinity system.

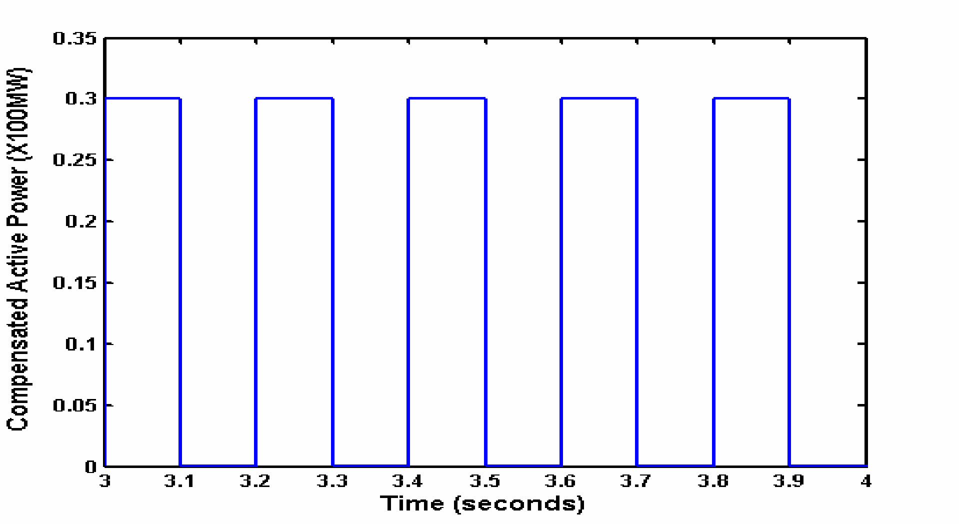


Fig. 3-16. Output active power (30MW) of the compensator

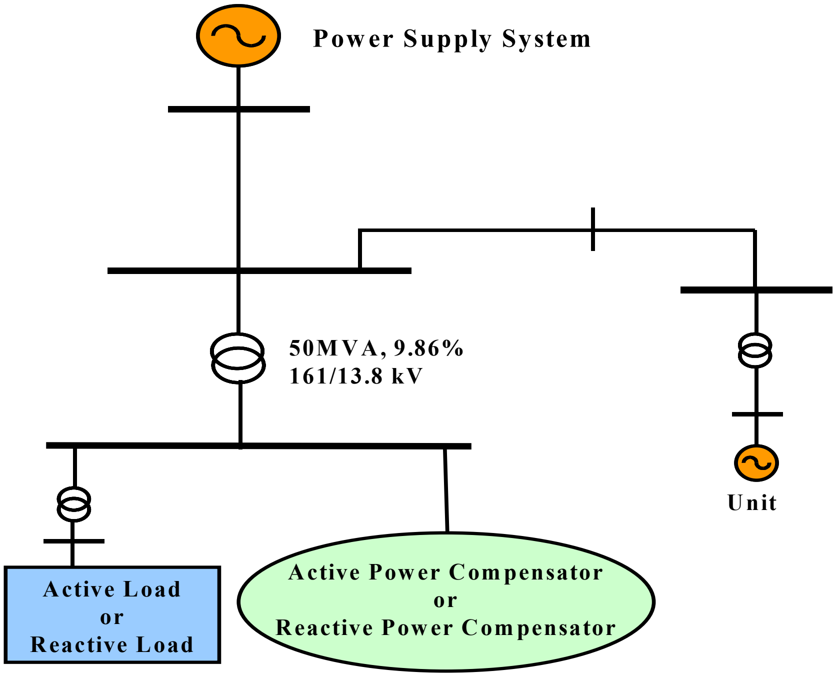


Fig. 3-17. Local one-line diagram

In Fig. 3-18, the 30MW active power can mitigate the voltage flicker by the 30MW active load completely. But the voltage fluctuation caused by 30MVAR reactive load, the 30MW active power cannot mitigate it thoroughly because of the X/R ratio issue. 30MVAR reactive power can cause about 3 times voltage drop of 30MW active load.

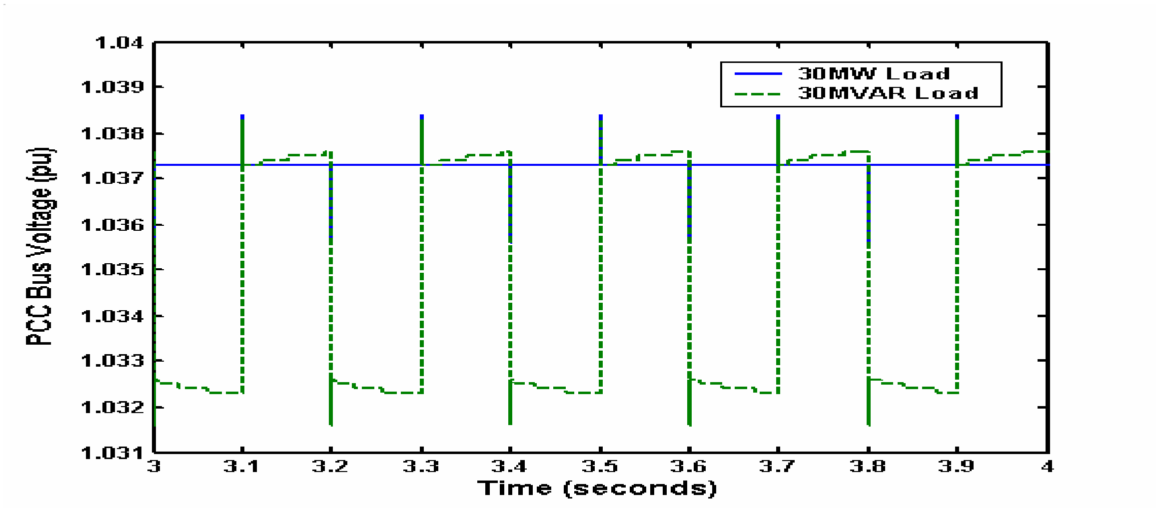


Fig. 3-18. Comparison of PCC bus voltage compensation effects by 30MW active power for 30MW or 30MVAR load

Fig. 3-19 is the bus angle control effect by the active power compensation. There is no bus angle oscillation caused by the 30MW active load. But the bus angle caused by 30MVAR reactive load increases after the compensation because of the phase opposite phenomenon shown in Fig. 3-7. 30MW active power compensation is another stimulator for this bus angle oscillation.

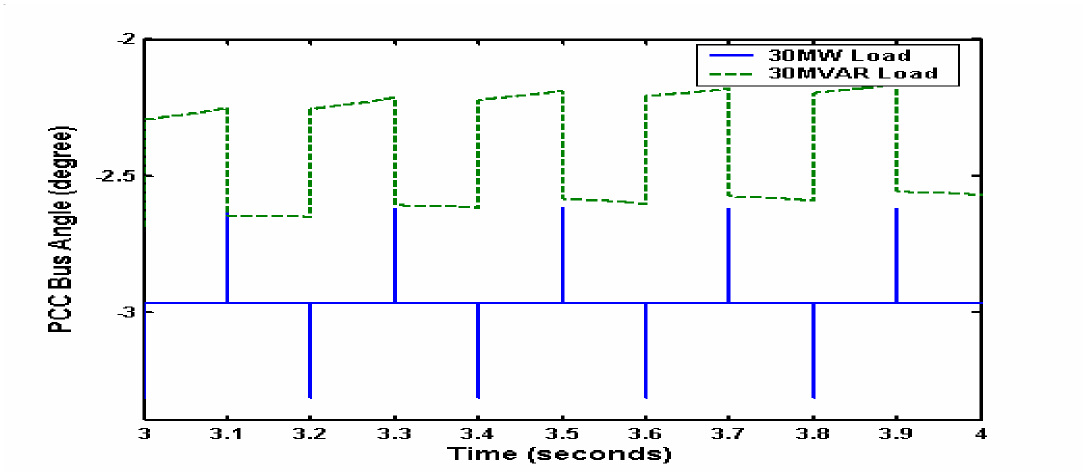


Fig. 3-19. Comparison of PCC bus angle compensation effects by 30MW active power for 30MW or 30MVAR load

Comparing Fig. 3-8, the active power compensation increases the nearby generator angle oscillation. The reason is also the opposite phase phenomenon shown in Fig. 3-7. 30MW active power compensation is also an extra stimulator for this generator oscillation when the 30MVAR reactive load is on.

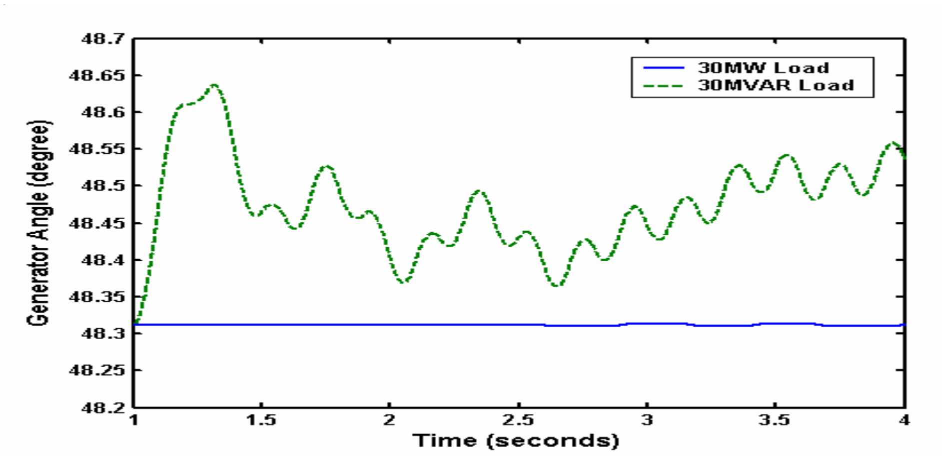
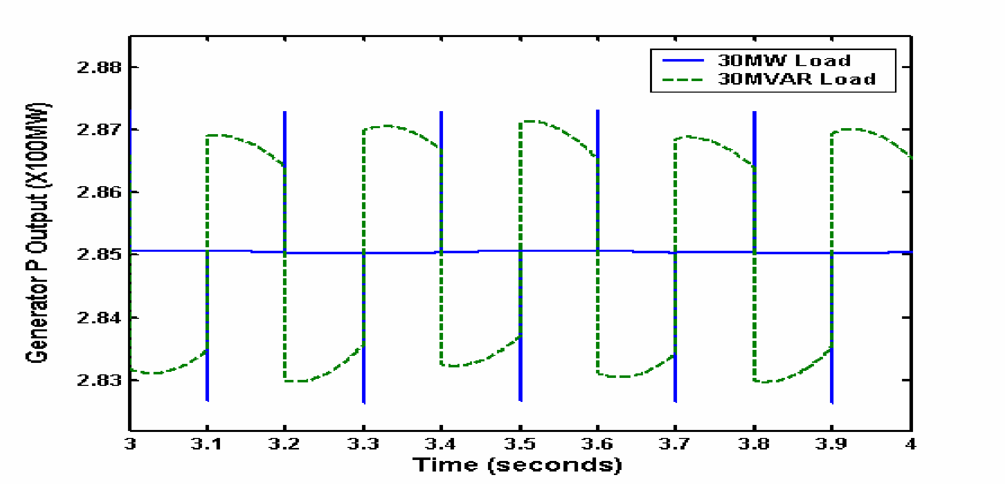


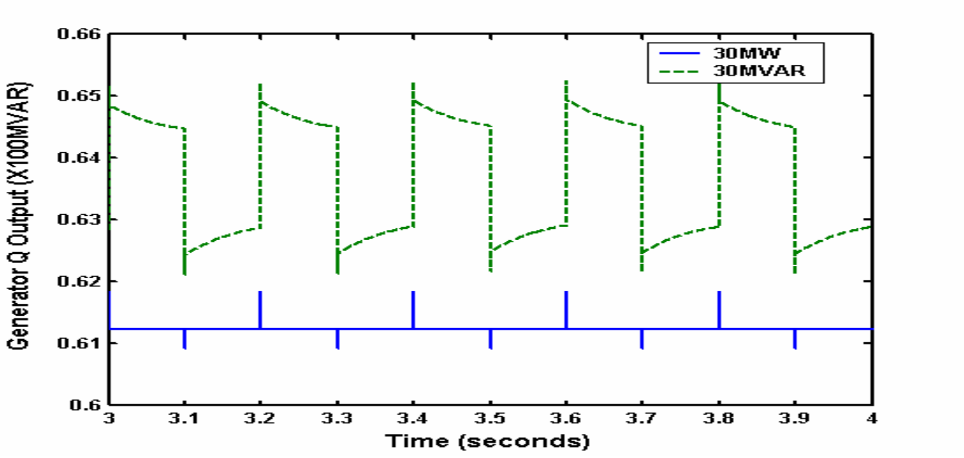
Fig. 3-20. Comparison of generator angle compensation effects by 30MW active power for 30MW or 30MVAR load

Because of the angle oscillation increasing in Fig. 3-19 and Fig. 3-20, generator output active power oscillates more than that before compensation when 30MVAR reactive load is on, shown in Fig. 3-21 (a).

Comparing the value in Fig. 3-10, the generator reactive power oscillation is smaller after the compensation when the 30MVAR reactive load is on, shown in Fig. 3-21 (b). The reason is that the voltage fluctuation is reduced as shown in Fig. 3-18.



(a) Comparison of generator P output



(b) Comparison of generator Q output

Fig. 3-21. Comparison of generator P or Q output compensation effects by 30MW active power for 30MW or 30MVAR load

The above study results show that the active power compensation can solve the power quality problems induced by active load perfectly. Either the voltage drop or the angle fluctuation can be mitigated thoroughly. But if active power compensation is applied to solve the power quality problems caused by reactive load, things are quite different. The active power compensation can mitigate the voltage flicker induced by reactive load, but the amount of compensated active power should be several times (similar to the X/R ratio) of the amount of reactive load to mitigate the voltage drop completely. The nearby generator reactive power output oscillation can be reduced because of the voltage control effects. For the reactive load, the voltage flicker mitigation control by active power compensation will increase the bus angle oscillation, thus increase the nearby generator angle oscillation and generator output active power oscillation.

Being a comparison, Fig. 3-22 to Fig. 3-24 show the control results of the power quality problems induced either by 30MW active load or 30MVAR reactive load by the pure reactive power compensation. In Fig. 3-22, we can see that reactive power compensation can improve the PCC bus voltage to the reference level for both the 30MM and 30MVAR load. But the reactive compensation cannot mitigate the PCC bus angle fluctuation caused by the 30MW active load even though it can mitigate the PCC bus angle fluctuation caused by 30MVAR load very well as shown in Fig. 3-23.

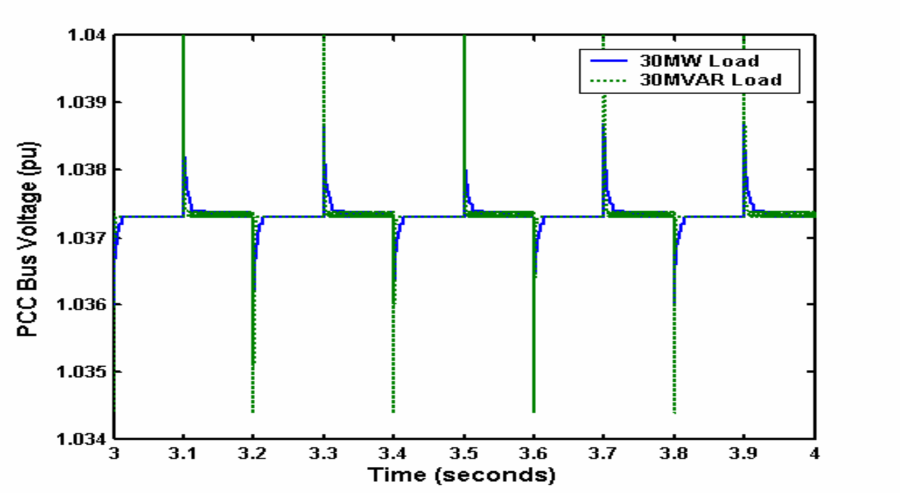


Fig. 3-22. Comparison of PCC bus voltage compensation effects by 30MVAR reactive power for 30MW or 30MVAR load

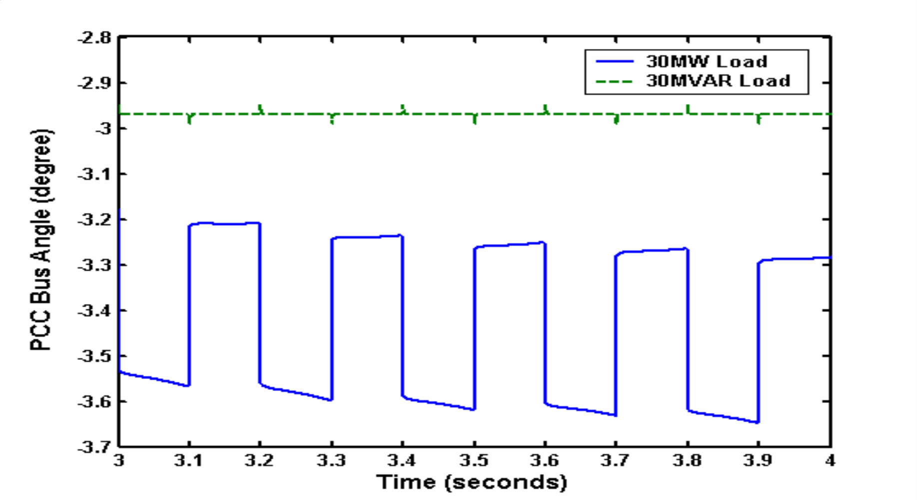


Fig. 3-23. Comparison of PCC bus angle compensation effects by 30MVAR reactive power for 30MW or 30MVAR load

In Fig. 3-24 we can see that the nearby generator active power output oscillation will be same or even worse by the pure reactive power compensation for the 30MW active load. But the control effect of nearby generator reactive power output is very well because of the good control effect of the PCC bus voltage for the 30MW active load as shown in Fig. 3-22. The pure reactive compensation effect for the 30MVAR reactive load is as good as that of the active power compensation for the 30MW active load.

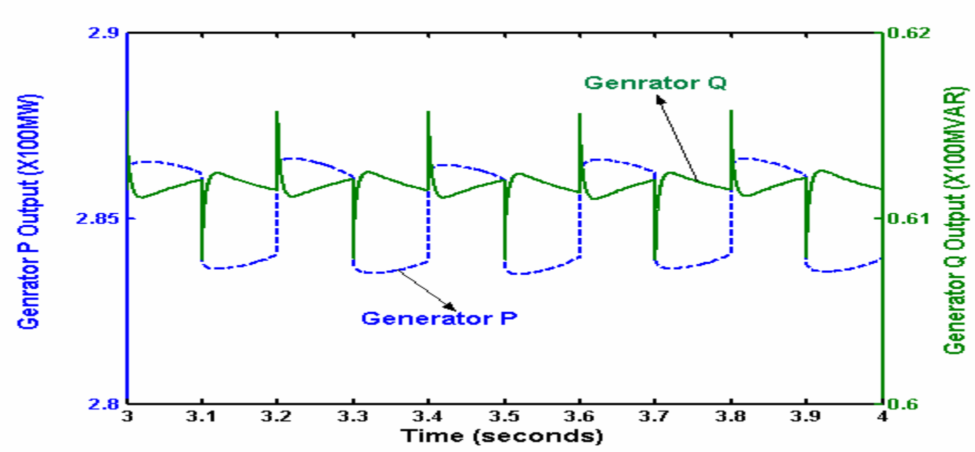


Fig. 3-24. Comparison of generator P & Q compensation effects by 30MVAR reactive power for 30MW load

According to the above study, if the power quality problems are caused by both the active load and reactive load, the coordination control of active power compensation and reactive power compensation should be applied. In this situation, FACTS/ESS can provide significant improvements in mitigating this kind of problems over more conventional compensation methods, e.g. STATCOM, because of its active and reactive power control capability.

3.5 EAF Induced Problems Solution by FACTS/ESS

3.5.1 Electric Arc Furnace Characteristics

The energy efficiency and economy makes the electrical arc furnace widely used equipment for production of steel. But the operation of an arc furnace can generate harmonics. Because the length of an electric arc and the arc power depend on the distance between the tip of the graphite electrode and the charge, the current and power due to an electric arc comprise stochastic components. The irregular shapes of metal charges, which mainly comprise scrap metals, contribute further to the stochastic character of the current and the power. The length of an electric arc also affects the voltage across the arc. But in existing furnaces, the electrodes are manually operated, and the lengths of the arcs vary with a degree of randomness. Consequently, the voltage across an arc varies typically over several cycles of the supply AC current. This causes the phenomenon of voltage flicker [46-50].

Both the harmonic currents and the voltage flickers caused by the operation of an electric arc furnace can affect the operation of other equipment or machines in the same factory. These may also spread to other factories in the same distribution system and incur adverse problems.

In a stiff system where the short circuit capacity is large, the problems of harmonics and voltage flickers may not pose series problems on the system. Nevertheless, some studies reported detection of the effect of voltage flicker from the operation of an electric arc furnace in one factory on the power line of another factory connected to another feeder. Furthermore, the study also discovered that the distribution network in the vicinity inherently reasons at the 5th harmonic due to the use of power capacitors at the substation.

The operation of an arc furnace does not only generate harmonics, but also voltage dips. The voltage across an arc varies because the lengths of the arcs vary with a degree of randomness. This causes the phenomenon of voltage flicker. Both the harmonic currents and voltage flickers caused by the operation of an EAF can affect the operation of other equipment or machines in the same factory or nearby factories in the same distribution system. In a strong power system where short circuit capacity is large, the power quality problems caused by an EAF may not be serious. But the story is quite different for today's bulk power systems because of their operation near limits [46-49].

Several studies reported detection of the effect of voltage flicker from the operation of an EAF on the power feeders in nearby factories. The studies also discovered that the neighboring distribution network inherently resonated an active oscillation [49-51]. As mentioned above, instantaneous fluctuations with large amplitudes of active and reactive power in EAF's are the main source of various power quality disturbances in an electric power system. Traditionally, for a mainly inductive supply system, power quality can be improved by adjusting reactive power and its fluctuations using reactive power control methods. But for the EAF load, only adjusting reactive power is not enough.

Power electronics capable of switching at high power have led to the applications of SVC's and STATCOM's. These devices have been able to solve the power quality problems in distribution and transmission systems by rapidly controlling reactive power [48-50]. But for the power quality problems caused by an EAF, things are quite different. Real power fluctuation can cause phase angle variations at critical buses. These phase angle variations and active power fluctuations can cause stability problems in the bulk power system [50]. Advances in both energy storage technologies and the necessary power electronics interface have made energy storage systems (ESS) a viable technology for high power utility. The power industry's demands for more flexible, reliable and fast active power compensation devices make the ideal opportunity for ESS applications [45, 53].

3.5.2 EAF Model in PSS/E

An accurate three-phase arc furnace model is needed for the purpose of harmonic analysis and flicker compensation. Since the arc melting process is a dynamic stochastic process, it is difficult to make a precise deterministic model for an arc furnace load. The factors that affect the arc furnace operation are the melting or refining materials, the melting stage, the electrode position, the electrode arm control scheme, the supply system voltage and impedance.

Many complex methods were proposed to more precisely represent EAF characteristics and study its impacts on power systems. These include the nonlinear resistance model, current source models, voltage source models, the nonlinear time varying voltage source model, nonlinear time varying resistance models, frequency domain models, and power balance models, etc, [46-48].

PSS/E power system simulation software we chose to use for this study has the ability to deal with a large power system. It contains a very large power equipment model library. However, there is no EAF model in it. The author created a practical arc furnace model to study the voltage flicker problem caused by EAF. The EAF model contains a resistor and a reactor in a random operation mode to display the dynamic characteristics of EAF. Because the focus here is to study the voltage flicker problem solutions by FACTS/ESS, a simple arc model will serve the purpose as long as the worst case that voltage fluctuation frequency and magnitude are reflected in the model. Our arc model can generate a variation of voltage at about 0.3 ~ 1% at a frequency around 5Hz. The harmonic problem is not considered. Fig. 3-25 shows the active and reactive power drawn by the EAF with a frequency of about 5Hz.

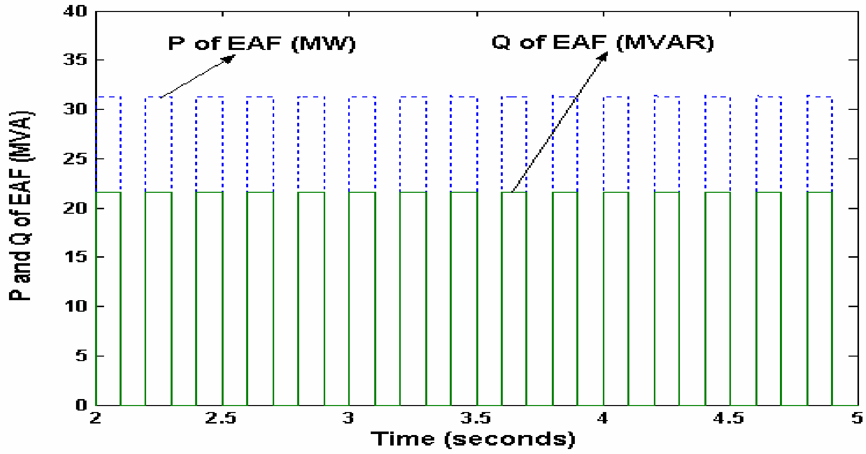


Fig. 3-25. The rapid change of active and reactive power drawn by EAF

3.5.3 Analysis of EAF Operation Impact on Bulk Power System

Fig. 3-26 shows the local system at Hoaganaes in TVA. Fig. 3-27 and Fig. 3-28 show the measured voltage and current at the steel mill. Fig. 3-29 is the real TVA Hoeganaes arc furnace sub-system.

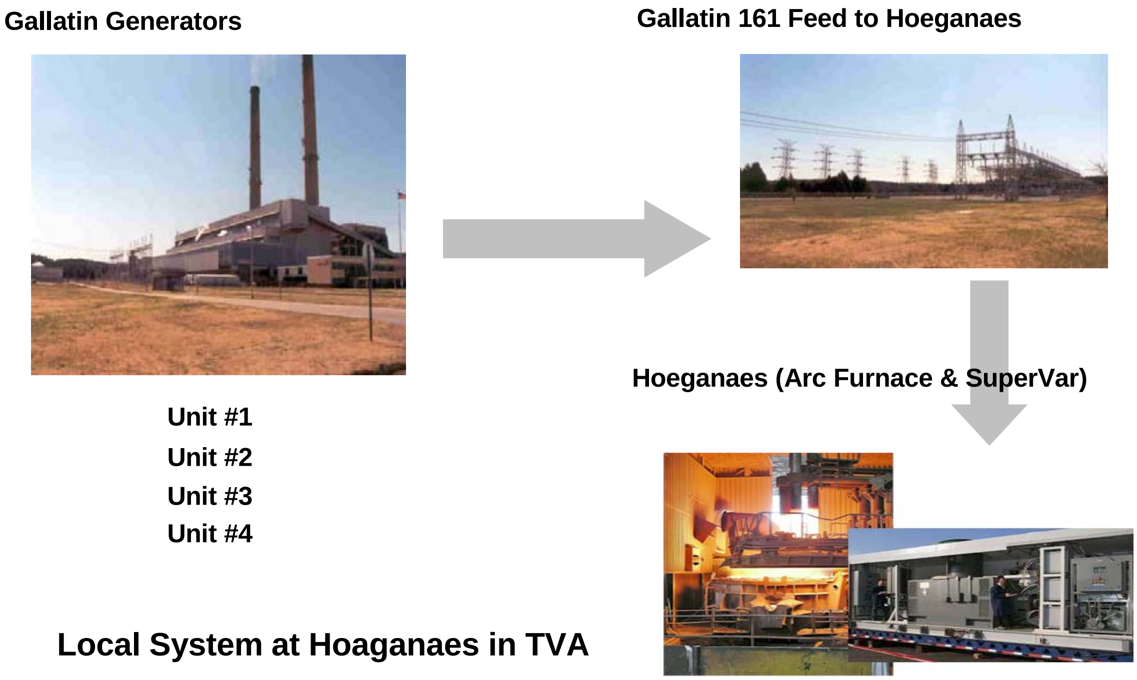


Fig. 3-26. Local system at Hoeganaes in TVA

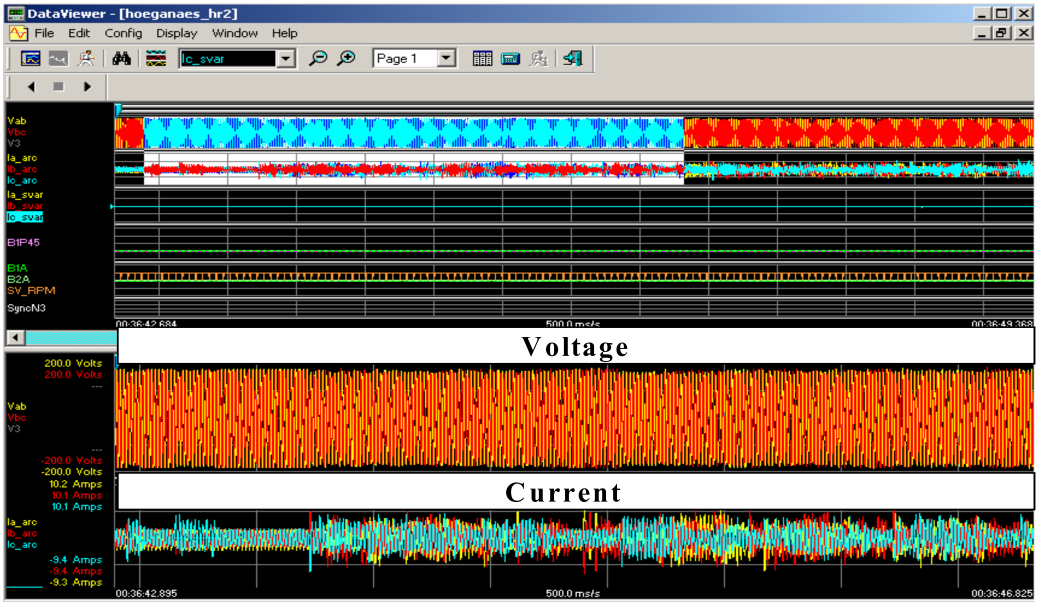


Fig. 3-27. Voltage and current measurements at steel mill using Nicolet Dataviewer

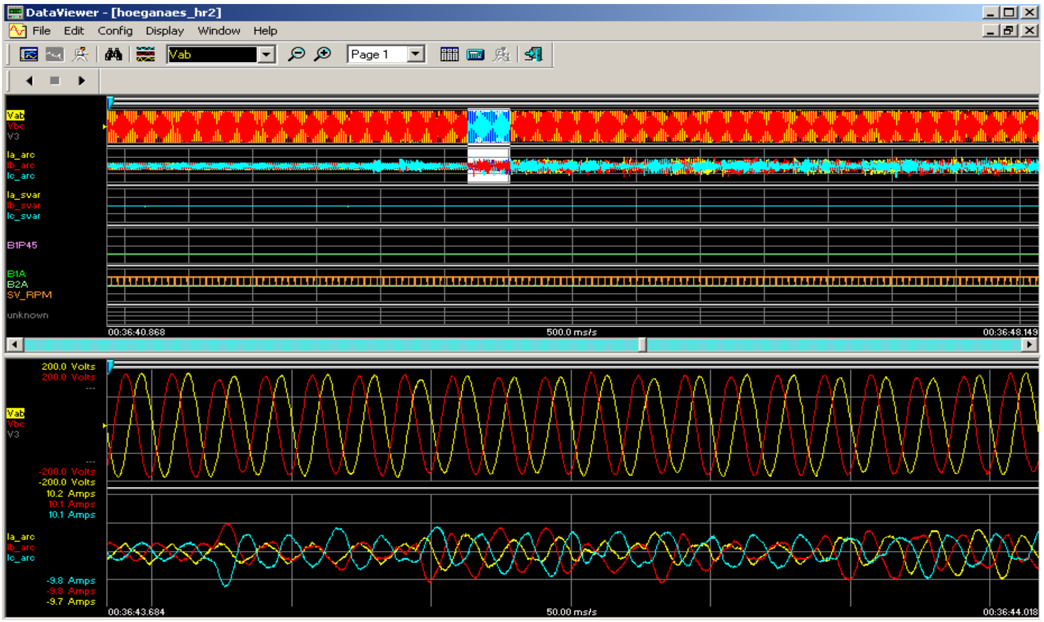


Fig. 3-28. Detailed current and voltage measurement waveforms using Nicolet Dataviewer

In this study, we use the Eastern U.S. system that contains the major portion of the NERC (North American Electric Reliability Council). The 40MVA EAF is installed in the substation that belongs to HOEGANAES Corp. Nearby, there is a steam station containing 4 generator units at Gallatin in Tennessee. Fig. 3-30 is the detail of the subject system structure.

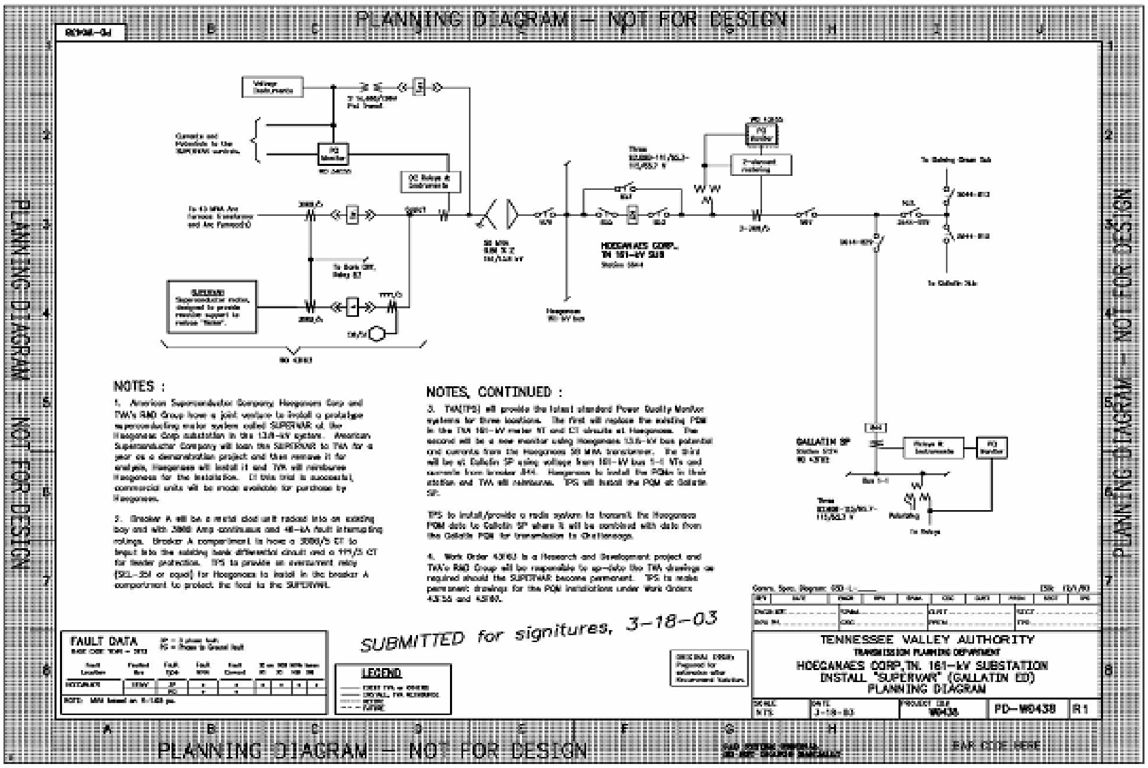


Fig. 3-29. The real TVA Hoeganaes arc furnace sub-system

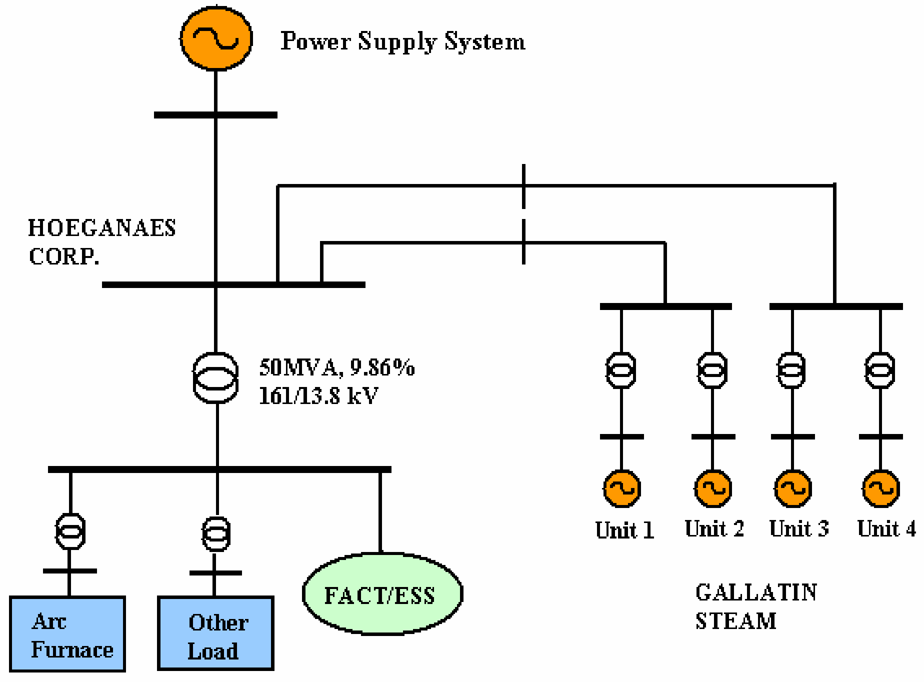


Fig. 3-30. One-line diagram of the subject system

Fig. 3-25 shows the active and reactive power drawn by the EAF with a frequency of about 5Hz. Fig. 3-31 shows the PCC bus voltage magnitude and angle fluctuation due to the EAF. Fig. 3-32 is the angle dynamic of Unit 4 generator at Gallatin Steam station, whose change is the same as Unit 3 but larger than the other two units. Fig. 3-33 is the output active and reactive power fluctuation of Unit 4 generator. It should be noted that Unit 1, Unit 2 and Unit 3 exhibit the same active power, reactive power, and angle fluctuation characteristics as that of Unit 4.

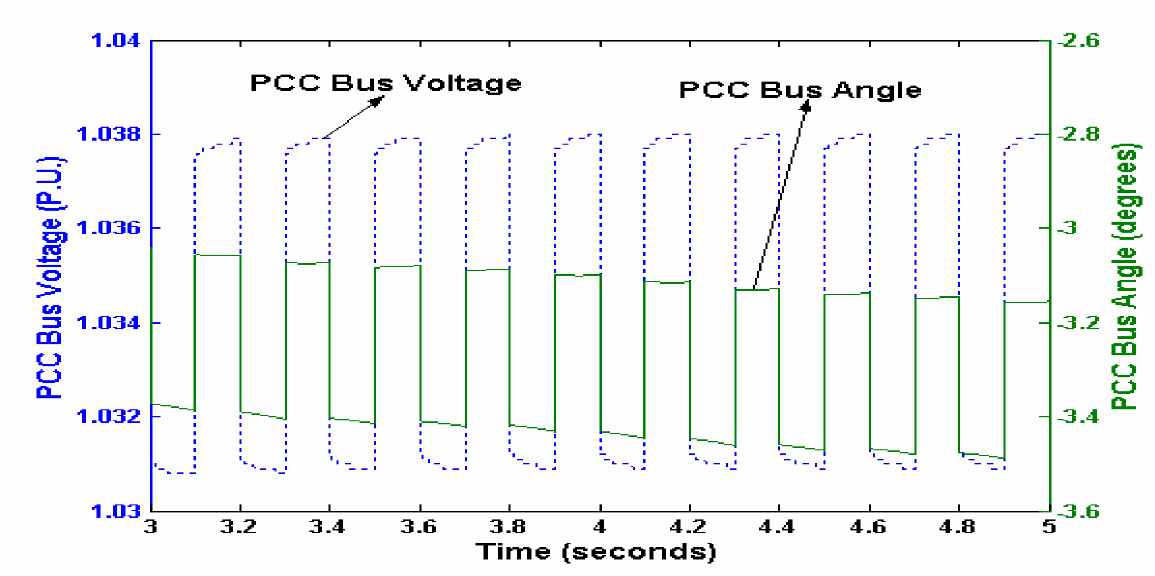


Fig. 3-31. PCC bus voltage and angle fluctuation

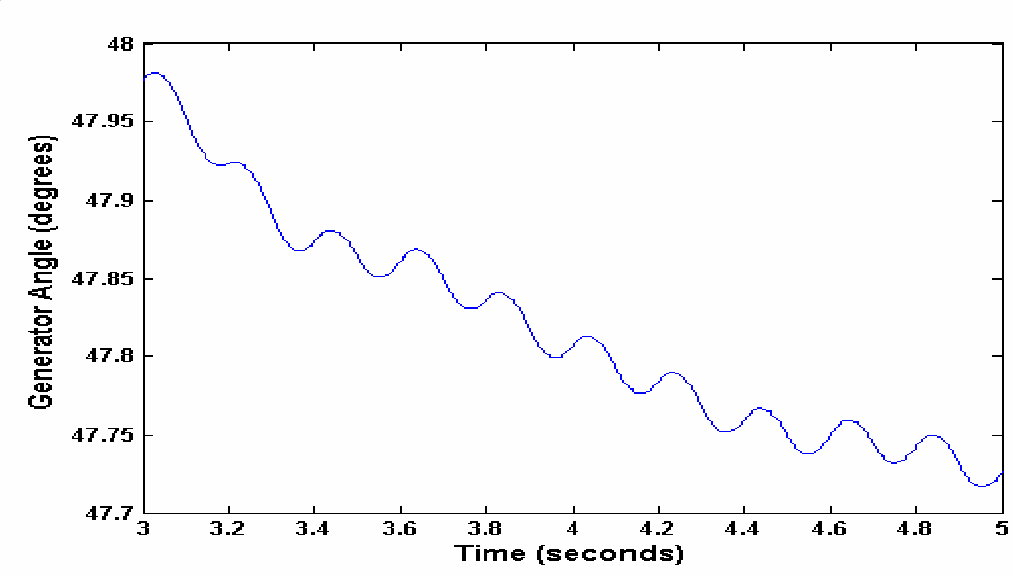


Fig. 3-32. Angle change of Unit 4 generator

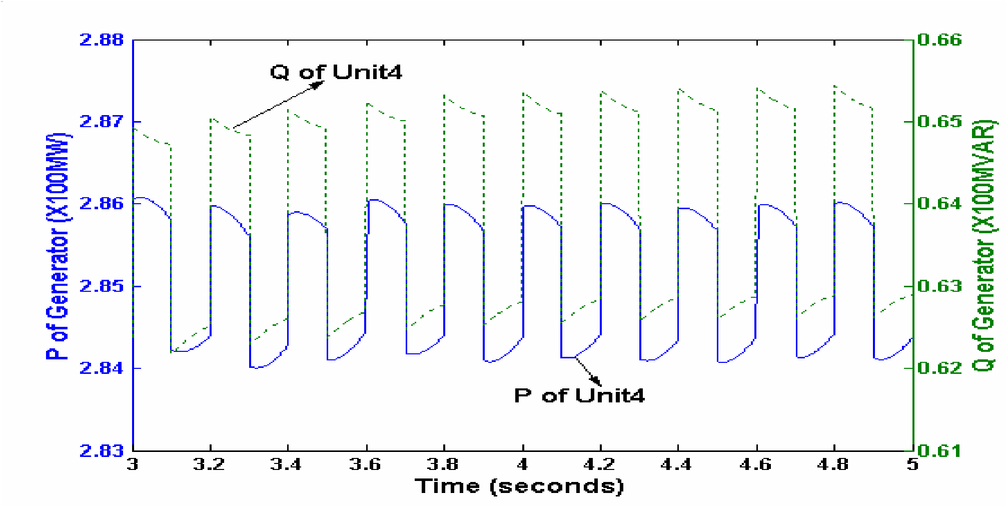


Fig. 3-33. Output active and reactive power of Unit 4 generator

From the above figures we can see that the operation of an EAF can cause not only the fluctuation of the voltage and angle of the PCC bus, but also cause the fluctuation of generator angle, generator output active and reactive power in the nearby system. Of course, the active and reactive power of generators oscillates at the EAF operation frequency as well. That can cause very serious power quality and stability problems in a bulk power system. In Fig. 3-34 and Fig. 3-35, we can check the ratio of voltage drop caused by 33MW active load and 24MVAR reactive load is about 0.458 in the real system. The level of PCC bus voltage angle change caused by 33MW active load is much larger than that caused by 24MVAR reactive load in Fig. 3-36.

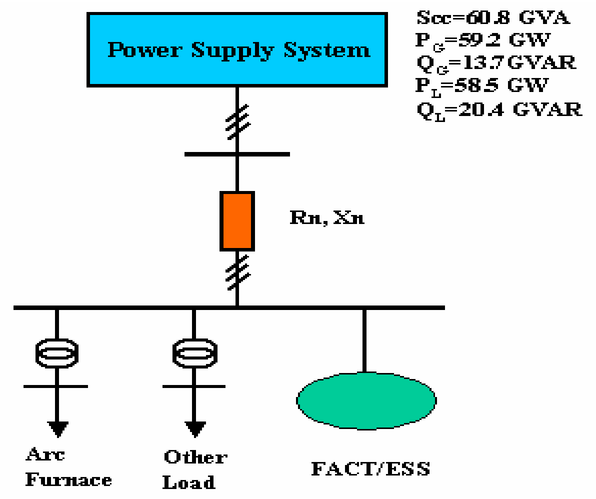


Fig. 3-34. PCC bus Thevenin equivalent circuit of the whole system

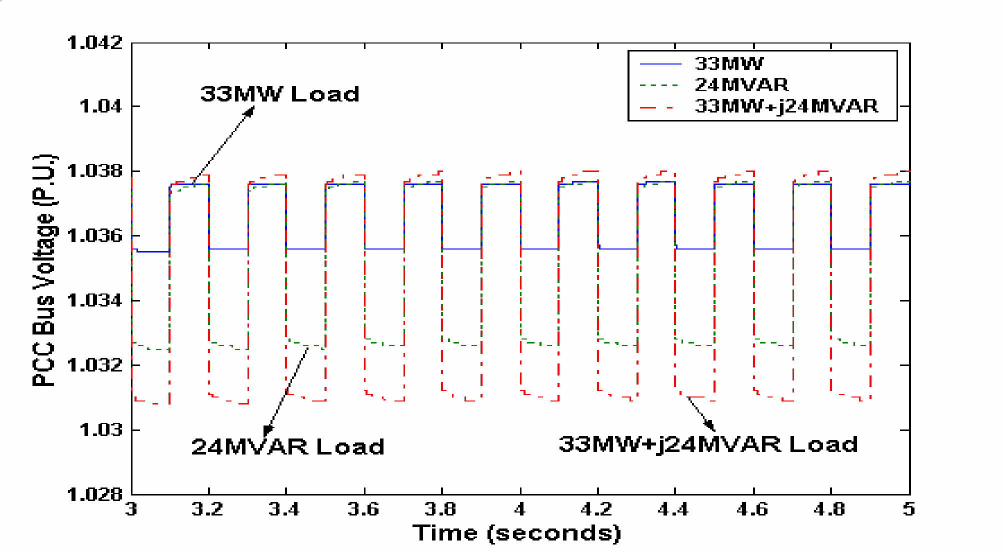


Fig. 3-35. Comparison of PCC bus voltage drop by active load (33MW), reactive load (24MVAR) and their combination (33MW+j24MVAR)

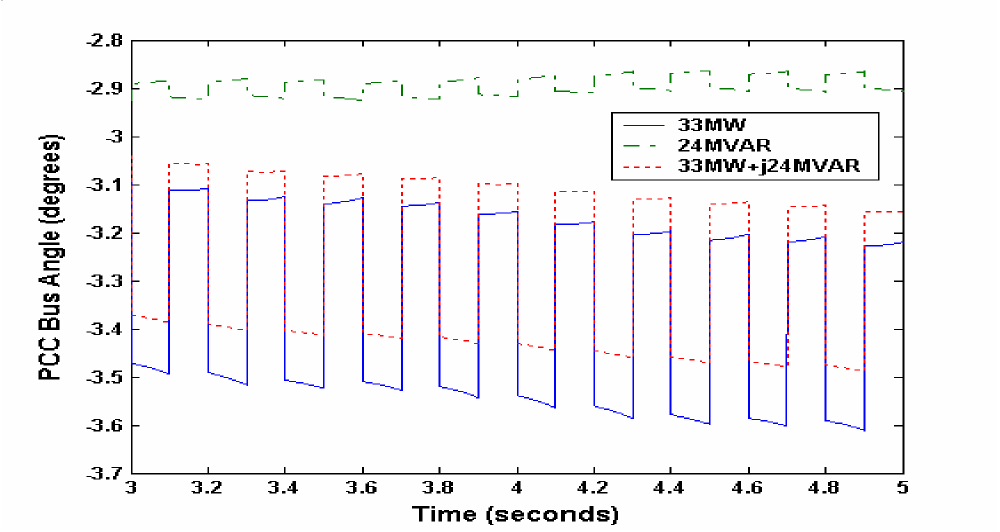


Fig. 3-36. Comparison of the PCC bus angle change by active load (33MW), reactive load (24MVAR) and their combination (33MW+j24MVAR)

Another interesting phenomenon is that the generator angle fluctuation caused by the combined 33MW+j24MVAR load is slightly less than the fluctuation caused by the 33MW active load alone. The reason is that the generator angle fluctuation caused by 33MW active load is not in phase with the fluctuation caused by the 24MVAR reactive load. Their trends are opposite in Fig. 3-37. A canceling effect occurs.

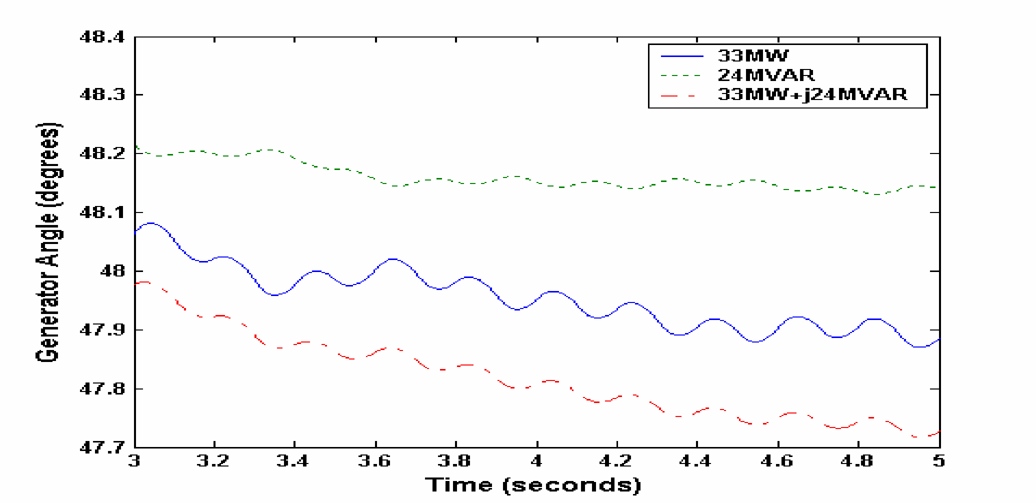


Fig. 3-37. Comparison of Unit 4 generator angle change caused by active load (33MW), reactive load (24MVAR) and their combination (33MW+j24MVAR)

3.5.4 EAF Induced Problems Solution by FACTS/ESS

The construction of the FACTS/ESS in this dissertation consists of three main parts: an energy storage system such as battery and SMES, a power converter, and a transformer. The converter produces a three-phase voltage at the primary winding of the transformer. This voltage can be varied in magnitude and phase with respect to the voltage on the high voltage side of the transformer. The reactive power exchanges between the converter and the ac system is controlled by varying the phase of the primary side voltage. The converter is effectively a STATCOM that has the added feature of controlling active power flow between its DC side and the AC side. Fig. 3-38 is the structure of FACTS/ESS [46].

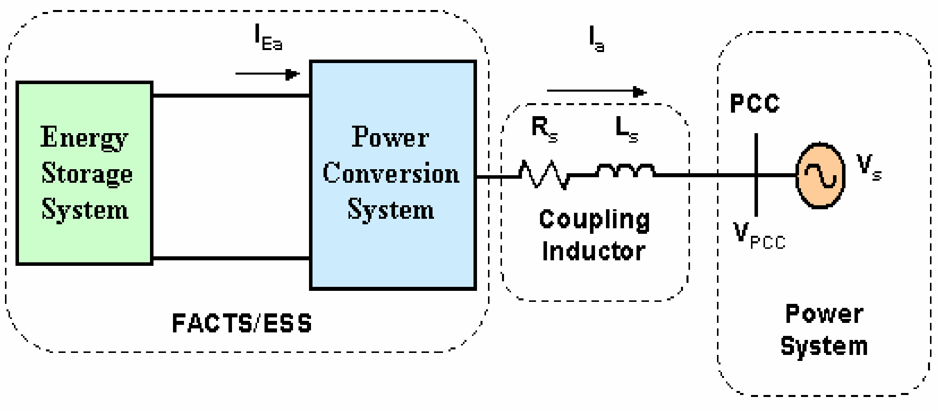


Fig. 3-38. The configuration of FACTS/ESS

In this study, the TVA plans to install an 8MVA FACTS/ESS device at the Hoeganaes substation. It may be a FACTS/SMES (also called D-SMES created by American Super Conductor) or a FACTS/SuperCap. The following study is based on the above background, which means the capacity of FACTS/ESS is 8MVA with 3.2MW active capacity.

Fig. 3-39 through Fig. 3-45 are the comparison of compensation effects by different devices such as STATCOM, FACTS/SMES and FACTS/BESS with 8MVA capacity. The FACTS/ESS devices operate in such a mode that they absorb active power from the system when the EAF draws no power, active or reactive, from the system. From these simulation results we can see that, even though the compensation effects are not substantial because of the limit of device capacity, the FACTS/ESS devices do compensate at an acceptable level. In the reactive power and voltage fluctuation aspect the FACTS/ESS has no obvious advantage over STATCOM, which are shown in Fig. 3-39 and Fig. 3-43. However, concerning active power, bus angle, and generator angle fluctuation control, the FACTS/ESS devices have obvious advantages over STATCOM. For example, FACTS/SMES and FACTS/BESS reduce the generator angle fluctuation substantially as shown in Fig. 3-41. The SMES and BESS offer a reduction in output active power fluctuation of Unit 4 over the reduction provided by STATCOM. Of course the FACTS/ESS devices cannot offer a significant advantage over the STATCOM in reducing the voltage flicker and generator reactive power output fluctuation.

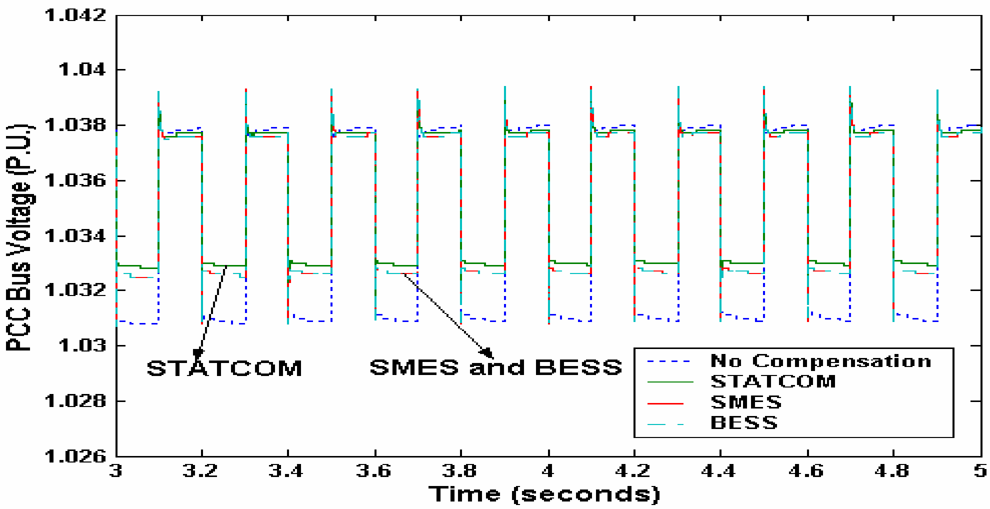


Fig. 3-39. Comparison of PCC bus voltage compensation effects by 8MVA FACTS/ESS

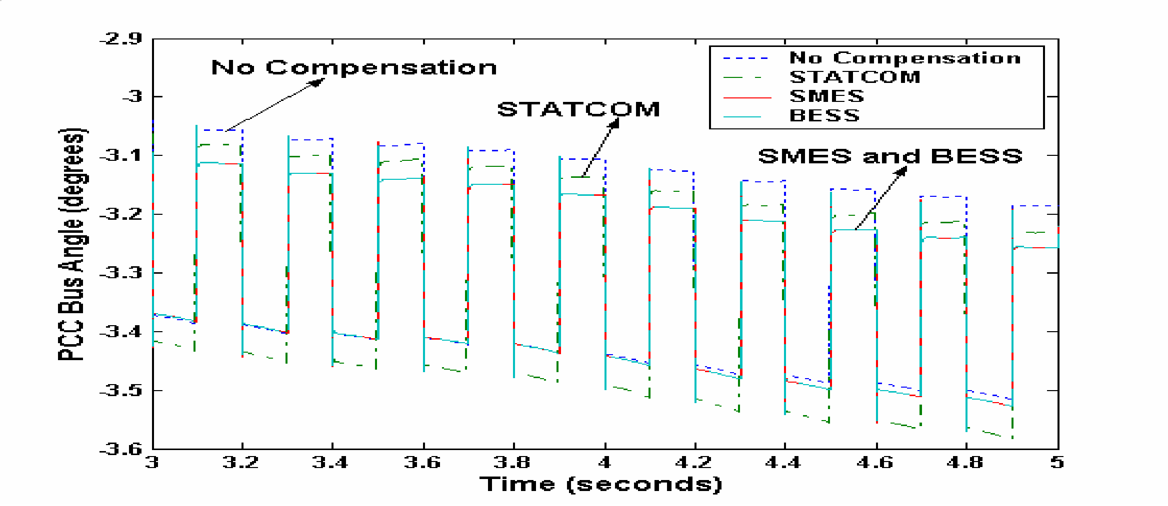


Fig. 3-40. Comparison of PCC bus angle compensation effects by 8MVA FACTS/ESS

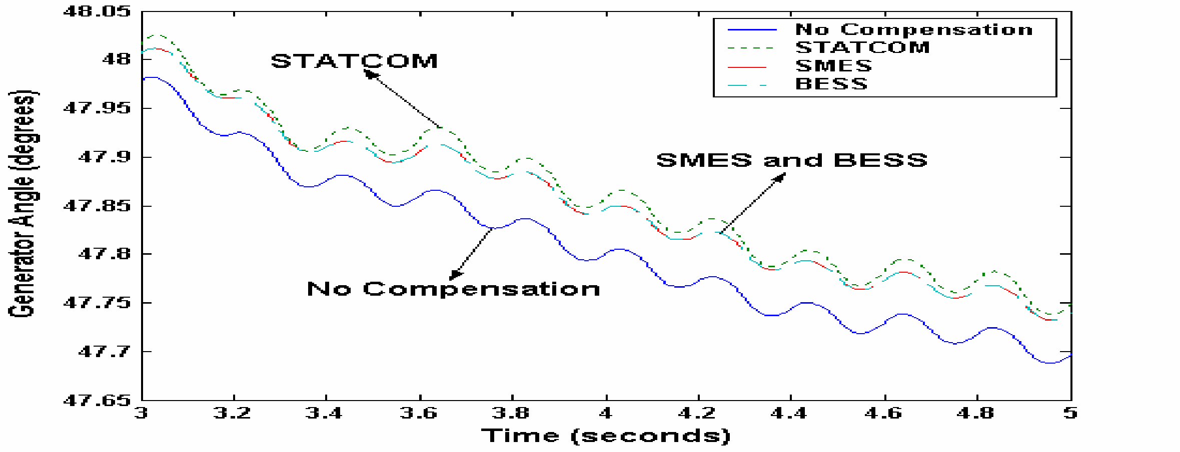


Fig. 3-41. Comparison of generator angle control effects by 8MVA FACTS/ESS

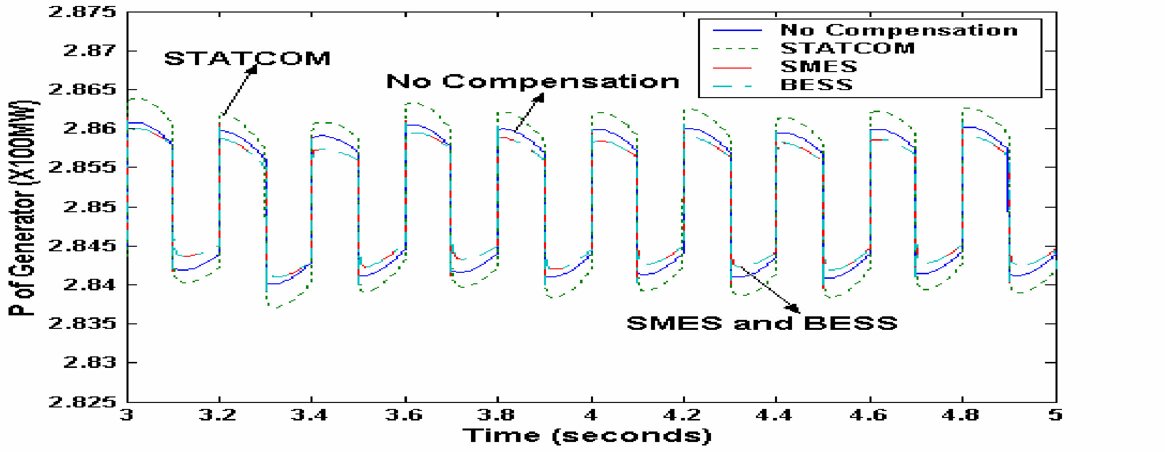


Fig. 3-42. Generator output active power control by 8MVA FACTS/ESS

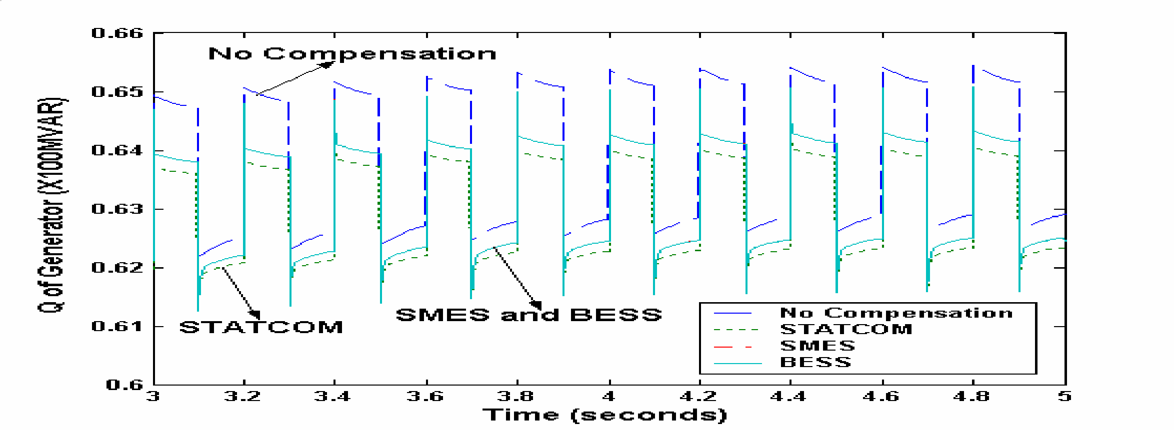


Fig. 3-43. Generator output reactive power control by 8MVA FACTS/ESS

Fig. 3-44 and Fig. 3-45 are the output active power and reactive power of FACTS/ESS. Of course, the active power output of STATCOM is zero. But its reactive power output is larger than that of FACTS/ESS to improve the voltage to a desired level.

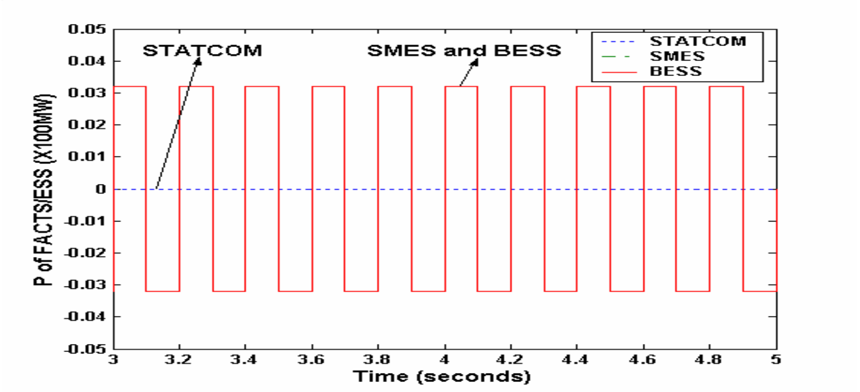


Fig. 3-44. Output active power of 8MVA FACTS/ESS

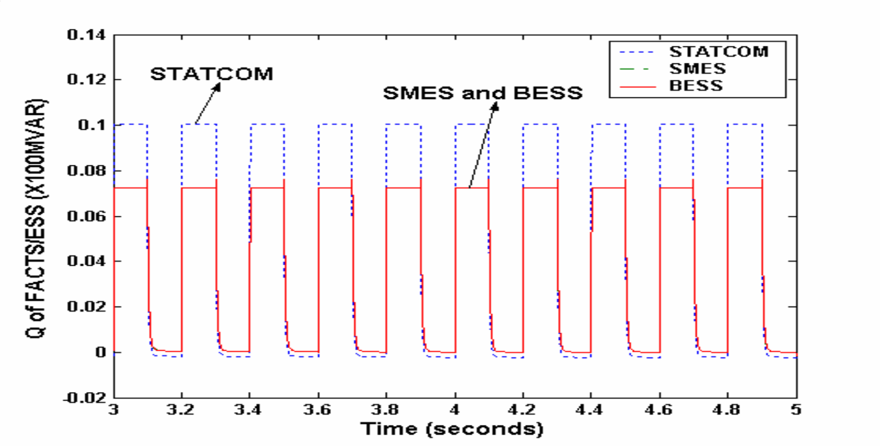


Fig. 3-45. Output reactive power of 8MVA FACTS/ESS

Fig. 3-46 through Fig. 3-48 show the simulation results when we use a FACTS/ESS with a capacity large enough (like 50 MVA) to compensate the EAF load. Here the capacity of FACTS/ESS is 50MVA with 20MW active capacity. The simulation results show that this high capacity FACTS/ESS provides satisfactory results. In Fig. 3-46 and Fig. 3-47, the FACTS/ESS devices perform better than STATCOM in mitigating the PCC bus voltage and angle fluctuation and generator angle swing.

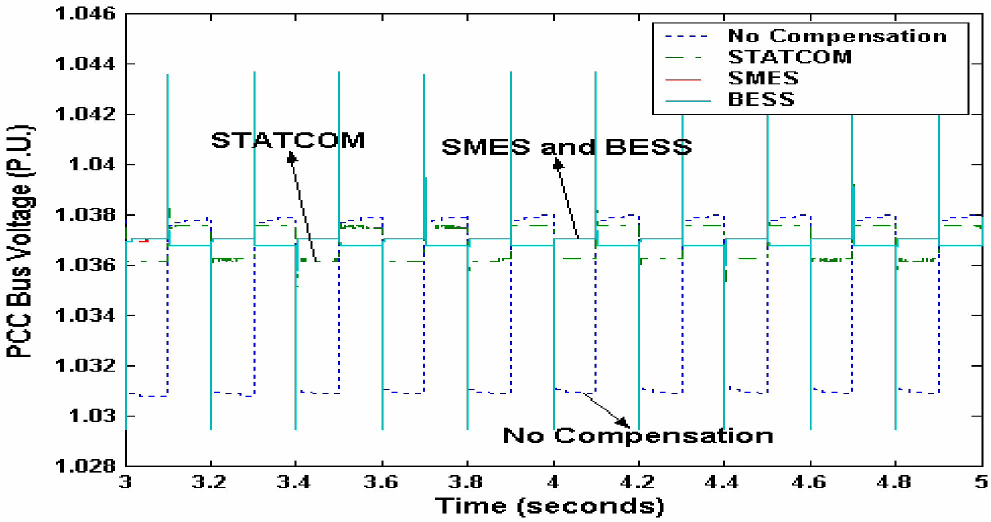


Fig. 3-46. PCC bus voltage control by 50MVA FACTS/ESS

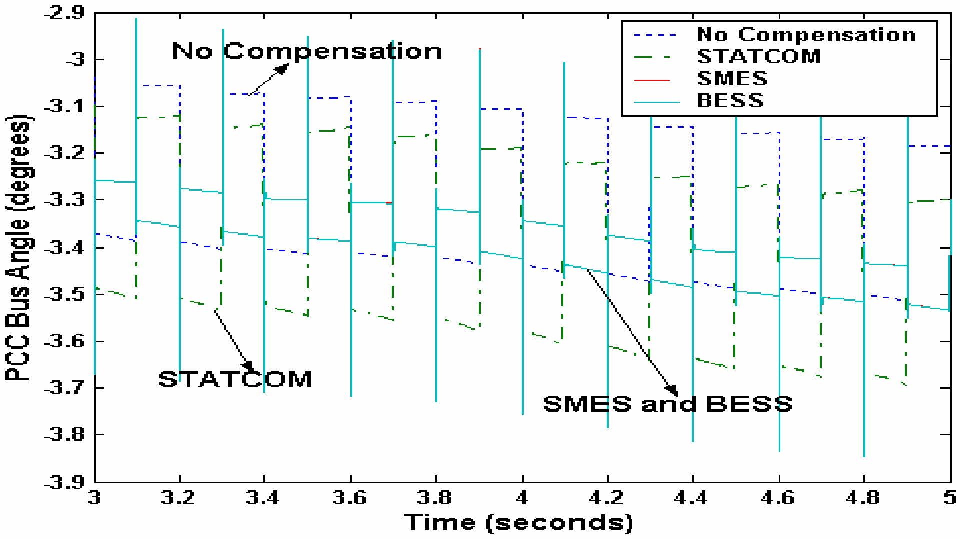


Fig. 3-47. PCC bus angle control by 50 MVAFACTS/ESS

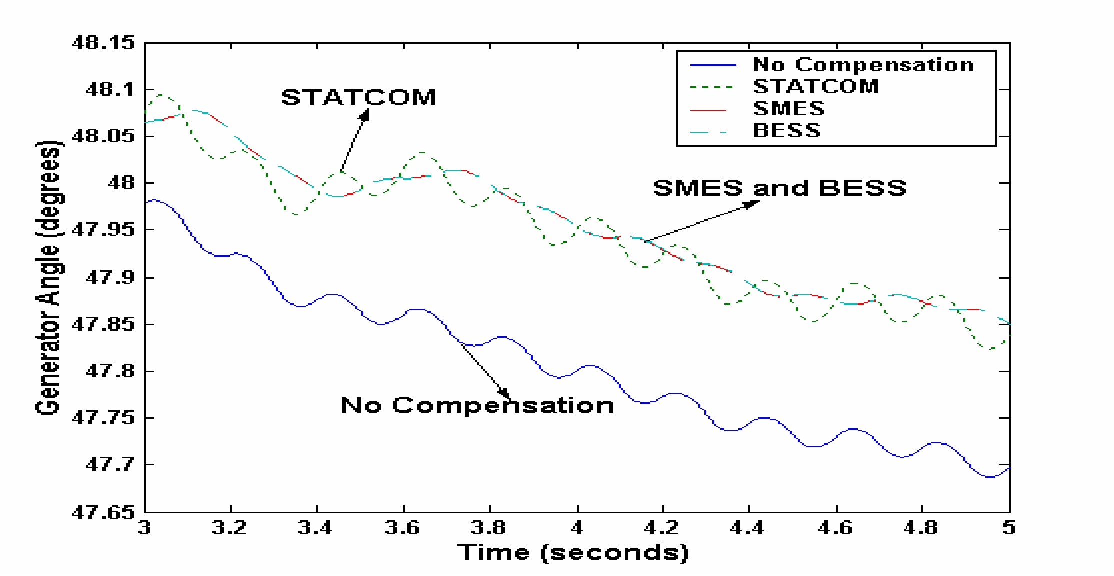


Fig. 3-48. Generator angle control by 50 MVA FACTS/ESS

3.6 Summary

Active load can be a source of power quality problems as well as the reactive load. In this study the author examine the effects of active and reactive load on the power quality in bulk power system. The focus of this study is the impact of pulsing active and reactive load on the PCC bus voltage and the operation of the generators in the vicinity system. The study results show that the impacts of active and reactive load on the power quality problems are different. Same amount of active load can cause more angle fluctuation than reactive load. On the contrary, same amount of reactive load can bring more voltage fluctuation than active load. This study also attempts to find the role of pure active power compensation in correcting the periodic active and reactive load induced problems in a bulk power system. The effect of pure reactive power compensation for same situation is also studied. The author analyzed how active load operation can affect a power system by giving a detailed discussion about the function of X/R ratio. The simulation results show that either the pure active or pure reactive power compensation method has its own limitation in solving the power quality problems caused by both the active and reactive load. The coordination of both active power compensation and reactive power compensation is an ideal method to solve the power quality problems caused by the combination of active and reactive load. In this situation, FACTS/ESS can provide significant improvements in mitigating this kind of problems over more conventional compensation methods, e.g. STATCOM, because of its active and reactive power control capability.

The operation of the electric arc furnace can cause power quality problems, especially as voltage flickers, to the power supply system to which it is connected. Nowadays, most utilities and power customers are facing the need to solve the power quality problem created by EAF. Some may falsely believe it is only the reactive power demand of the EAF that causes the voltage flicker. This mistake stems from the assumption the X/R ratio is determined mainly by the up-stream transformer or transmission line, which is typically larger than 10. Indeed, for such a high X/R ratio, active power can play a minor role in boosting the bus voltage. The author have shown the discussion of X/R ratio should be from the point of view of the whole system, which means R and X are not just the impedance of the upper transformer or line. They should be the Thevenin impedance seen from the PCC bus of the whole system. In this study, the active power drawn by EAF also contributes obviously to the voltage flicker. The reason is that actual system X/R ratio is within a range ($X/R \approx 3$ in our sample system) that makes the active power load influencing the voltage drop of the PCC bus.

The FACTS with ESS has advantages over FACTS alone by supporting the active and reactive power at the same time. In this dissertation, the author analyzed the effects of the FACTS/ESS in mitigation of voltage flickers caused by EAF. A practical EAF model is created to simulate the change of active and reactive powers drawn by an EAF. Different operation modes of the FACTS/ESS have been discussed. The simulation results were presented. The study showed that FACTS with ESS can be more effective than using the FACTS devices alone.

Chapter 4. Bulk Power System Low Frequency Oscillation Suppression by FACTS/ESS

4.1 Background

Containing large amount of different dynamic devices, low frequency oscillations in some parts or between parts of the interconnected power systems are commonly experienced in modern power systems. The low frequency oscillations in power systems take place as the synchronous generators swing against each other.

The frequency range of these oscillations is from 0.1 to 2.5 Hz. It is related to the dynamic power transfer between areas. At times, the oscillations may continue to grow, causing the instability of power systems. There are two types of such oscillations referred to as local mode and inter-area mode, corresponding to a single-machine-to-infinite-bus structure, and those occur in interconnected power systems, respectively [64, 65].

Although a number of ways are available for damping the low frequency oscillations in power systems, the power system stabilizer (PSS) is the most commonly used one. It operates by generating an electric torque in phase with the rotor speed. In most cases, the PSS works well in damping oscillations [77, 79]. However, because the parameters of PSS are tuned by the original system parameters, its control has less flexibility, which means the control results are far from ideal if the operating conditions and/or structures of the system change [59].

Other modern controllers used to damp the power system oscillation may include high-voltage dc (HVDC) lines, static var compensators (SVCs), thyristor-controlled series capacitors (TCSCs), and other such flexible ac transmission system (FACTS) equipments. FACTS devices have the advantage of flexibility of being located at the most suitable places to achieve the best control results [59, 61-64].

FACTS/ESS technology has the advantages in both energy storage ability and flexibility of its power electronics interface. FACTS/ESS technology offers an alternative way in damping low frequency oscillations. FACTS/ESS has been employed due to its capability to work as active and reactive power generation and absorption systems. Besides the task of voltage control, it may also be applied to improve the transmission capability and system stability [57, 67, 68, 72, 73, 74, 75, 76, 78].

4.2 Analysis of Low Frequency Oscillation in Bulk Power System

The dynamic equation of the one-machine-to-infinite-bus system in Fig. 4-1 is given as follows [65].

$$\begin{cases} M\dfrac{d\omega}{dt} = P_m - P_e - D(\omega - 1) \\ \dfrac{d\delta}{dt} = \omega - 1 \end{cases} \tag{4-1}$$

In which, M is generator inertia, D is the damping factor, δ and ω are the generator angle and speed respectively. The generator active power output is give as:

$$P_e = \frac{E'U}{X_\Sigma}\sin\delta \tag{4-2}$$

Where X_Σ contains x_d' and the impedance of transformer and line.

The standard eigenfunction of equation (4-1) is follows,

$$p^2 + 2\xi\omega_n p + \omega_n^2 = 0 \tag{4-3}$$

Where,

$$\omega_n = \sqrt{\frac{K}{M}} \tag{4-4}$$

Which is the natural oscillation frequency when there is no damping (D=0). In (4-4), the synchronizing factor K is defined as,

$$K = \frac{E'U}{X_\Sigma}\cos\delta_0 \tag{4-5}$$

Here δ_0 is the generator angle.

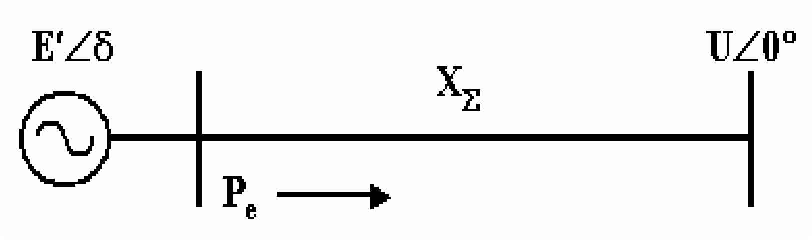


Fig. 4-1. One-machine-to-infinite-bus system

The above equations indicate the generator rotor angle deviation $\Delta\delta$ will oscillate against the infinite system at the frequency ω_n during the dynamic period after the disturbance. The oscillation will decrease if there is damping (e.g. D≠0).

If we simplified a multi-machine power system to the following quasi-second-order system shown in Fig. 4-2, we can have the following similar dynamic equations. Here p is d/dt in Fig. 4-2.

$$\begin{bmatrix} \Delta\dot{\boldsymbol{\delta}} \\ \Delta\dot{\boldsymbol{\omega}} \end{bmatrix} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{D} \end{bmatrix} \begin{bmatrix} \Delta\boldsymbol{\delta} \\ \Delta\boldsymbol{\omega} \end{bmatrix} \tag{4-6}$$

Where $\mathbf{K} = \frac{\partial P_e}{\partial \delta} = \mathbf{K}_1$, called synchronous torque factor matrix. $\mathbf{I}$ is the unit matrix. $\mathbf{M}$ and $\mathbf{D}$ are the inertia and damping factor matrix respectively.

The standard eigenfunction of (4-6) will be given in (4-7).

$$\mathbf{M}\Delta\ddot{\boldsymbol{\delta}} + \mathbf{D}\Delta\dot{\boldsymbol{\delta}} + \mathbf{K}\Delta\delta = \mathbf{0} \tag{4-7}$$

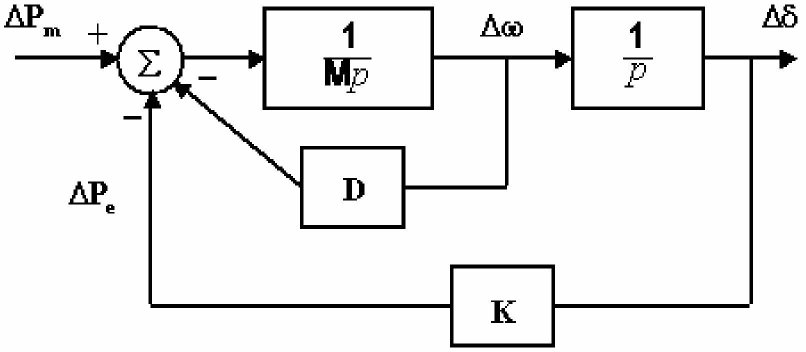


Fig. 4-2. Simplified multi-machine power system function

We can roughly analyze the low frequency oscillation in a multi-machine system the same way as in the above one-machine-to-infinite-bus system. But for a very detailed analysis, the whole system linearized state equation must be used. Analysis schemes such as SMA (selective modal analysis) and AESOPS (analysis of essential spontaneous oscillation in power systems) may be necessary [65].

As we assuming the disturbance in the power system is considerably slight, the whole system can be linearized around a given operating point, where the time derivatives of state variables are exclusively expressed in the terms of the state variables. Therefore Equation (4-6) can also expressed in the following detailed linearized state equation,

$$\dot{\mathbf{X}}=\begin{bmatrix}\Delta\dot{\partial}_1\\ \vdots\\ \Delta\dot{\partial}_n\\ \Delta\dot{\omega}_1\\ \vdots\\ \Delta\dot{\omega}_n\end{bmatrix}=\begin{bmatrix} & \boldsymbol{0}_{nxn} & & & & \boldsymbol{I}_{nxn} & \\ \frac{-K_{11}}{M_1} & \frac{-K_{12}}{M_1} & \cdots & \frac{-K_{1n}}{M_1} & \frac{-D_1}{M_1} & & \\ \vdots & \vdots & \vdots & \vdots & & \ddots & \\ \frac{-K_{n1}}{M_n} & \frac{-K_{n2}}{M_n} & \cdots & \frac{-K_{nn}}{M_n} & & & \frac{-D_n}{M_n}\end{bmatrix}\begin{bmatrix}\Delta\partial_1\\ \vdots\\ \Delta\partial_n\\ \Delta\omega_1\\ \vdots\\ \Delta\omega_n\end{bmatrix}=\mathbf{A}\bullet\mathbf{X} \qquad (4\text{-}8)$$

In (4-8), M_i and D_i are rotor inertia and damping coefficient; I_{nxn} is n order unit matrix. There are n-1 conjugate complex roots (complex conjugate pairs or eigenvalues) in (4-8), which reflect the relative oscillations of those n generators against each other in the system. Those oscillations are electromechanical mode oscillation. The impact of FACTS/ESS output on eigenvalues of the whole system is given in the matrix in equation (4-8) for the cases of different FACTS/ESS location and different control parameters.

For a weak power system, there must exist one or several complex conjugate pairs with poor damping low frequencies from equation (4-8). It is obviously the steady-state stability of this power system depends mainly on the behaviors of these modes. If an additional damping effect can be imposed on these modes, which means that a shift to the negative direction in the real part of these modes, obtained by installation of FACTS/ESS devices, the stability of this system will be enhanced.

In equation (4-2), when X_Σ is small, K in equation (4-5) is large, thus the value ω_n in (4-4) will be high. That means if the electrical distance between generators is small, the generators will oscillate at a high frequency. Generally, if the oscillation frequency is higher than 1Hz, it could be viewed as generator oscillation within a same area, or local mode (plant mode). If the oscillation frequency is low (around 0.2~0.5 Hz), it is classified as inter-area oscillation mode.

The researched Nashville area is within the TVA system shown in Fig. 4-3. In this area, there are about 4 generator groups located at Cumberland, Gallatin, Kingston, and Wilson. Low frequency oscillation has been monitored among these generator groups after a disturbance. We select one generator from each dynamic cluster (group) as a representative, which are Unit 1 at Cumberland, Unit 2 at Gallatin, Unit 3 at Kingston, and Unit 4 at Wilson. The disturbance in this study is a 0.05 cycles three-phase short circuit fault at north Nashville (see Fig. 4-3). During the fault, there is no bypass of the FACTS/ESS devices. In this study, we still use the Eastern U.S. System model. The system buses range from 765 kV to distribution level.

As an example, Fig. 4-4 shows the generator angle oscillations of the 4 generator-units at the 4 locations after a disturbance. The oscillation frequency is about 0.6 Hz. Fig. 4-5 is the relative angle of the generators in other three areas (Unit 1, Unit 2 and Unit 3) against the one in the Wilson area (Unit 4). Low frequency oscillation phenomena are found in these figures.

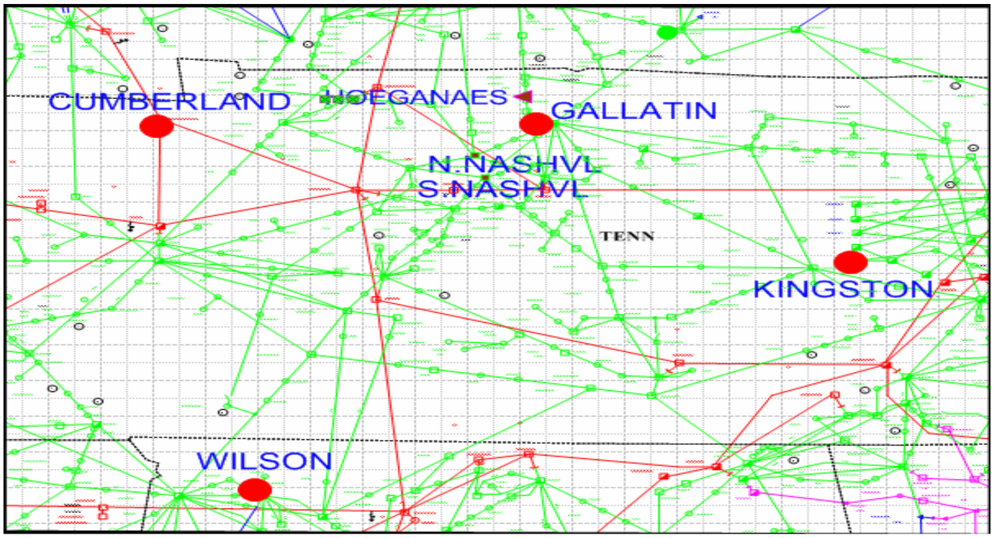


Fig. 4-3. TVA system one-line-diagram at Nashville area

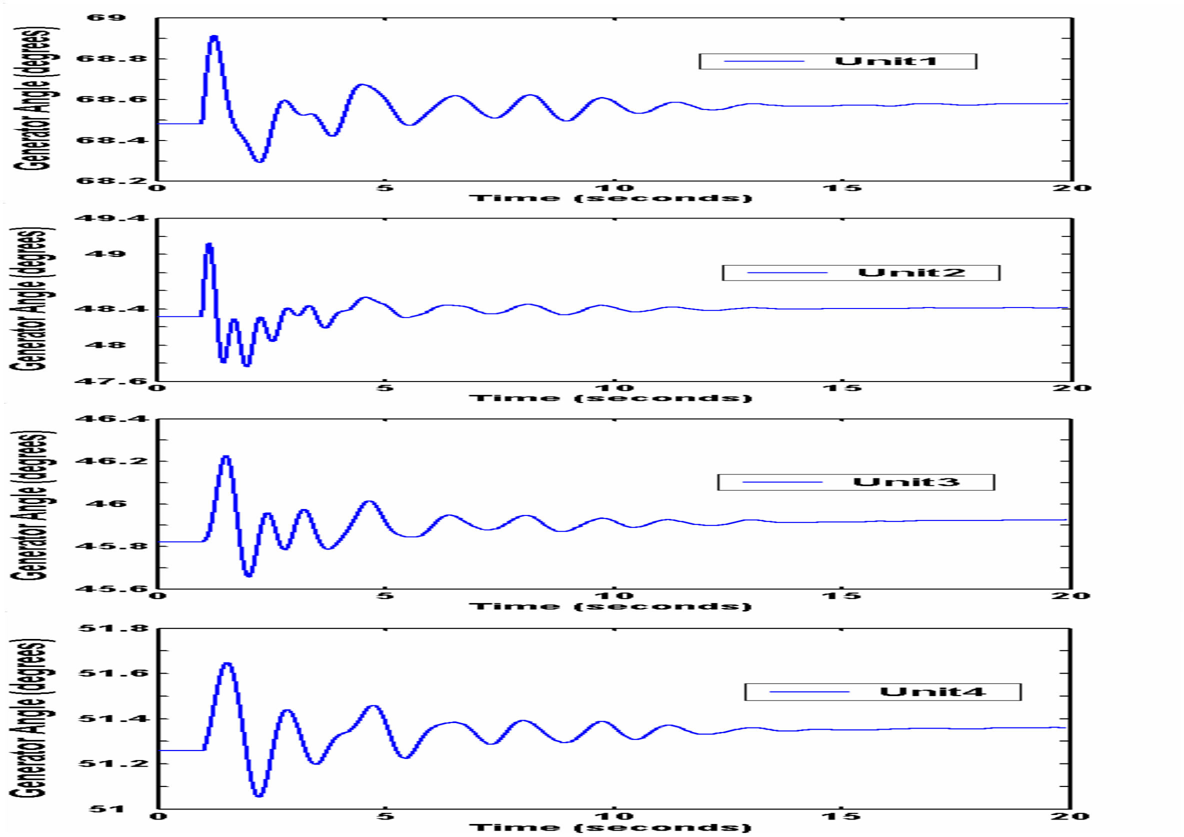


Fig. 4-4. Generator angle oscillations in the 4 different areas

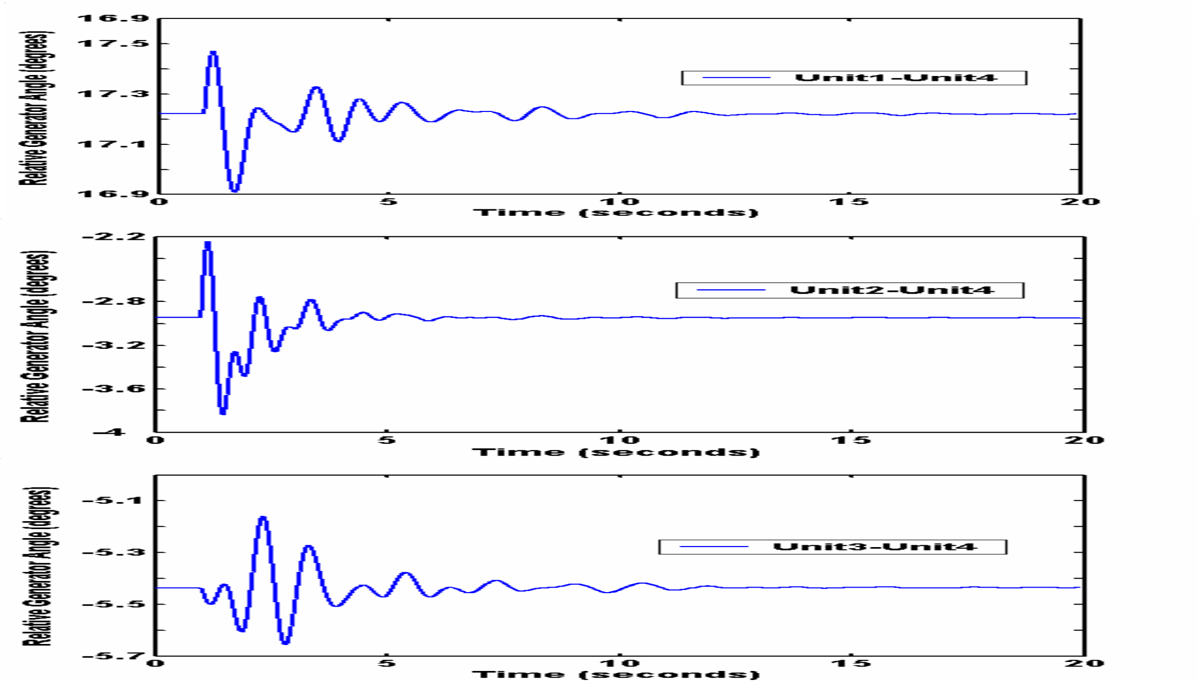


Fig. 4-5. Relative generator angle of Unit 1 (Cumberland), Unit 2 (Gallatin), and Unit 3 (Kingston) against Unit 4 (Wilson)

In the same group, generators have no relative oscillation against each other as shown in Fig. 4-6. We selected 4 generators in the group at Wilson naming them Gen1, Gen2, Gen3 and Gen4. Fig. 4-6 is the relative generator angle of the above 4 generators against Unit 4 in the same group. We can see that there is no relative oscillation. The generators from different area groups have low frequency oscillation against each other after a disturbance.

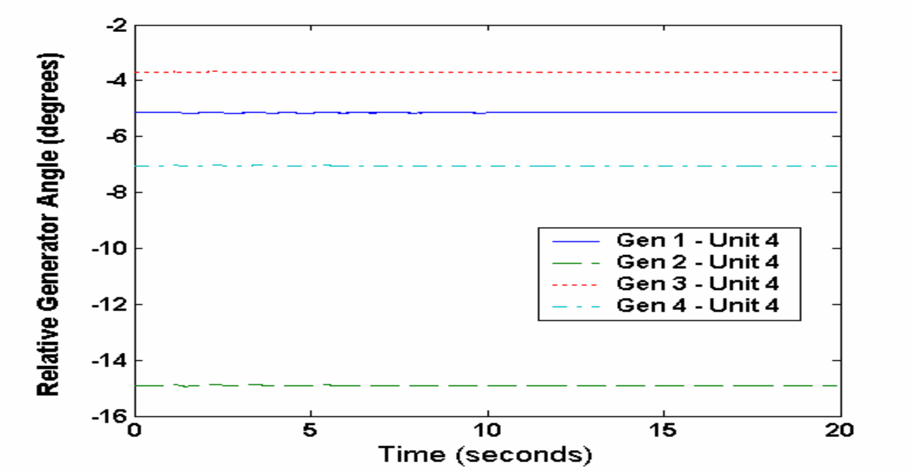


Fig. 4-6. Relative generator angle against Unit 4 in the group No. 4 at Wilson

Fig. 4-7 is the reactive power output of the four generator-units. There is no oscillation of the generator reactive power. The reason lies in that the terminal voltage of each one does not change violently. The reactive power of Unit 1 and Unit 2 changes a little to control the local voltage during and after the fault. Reactive power of Unit 3 and Unit 4 has no change either during or after the fault which means the local voltage does not change much at all.

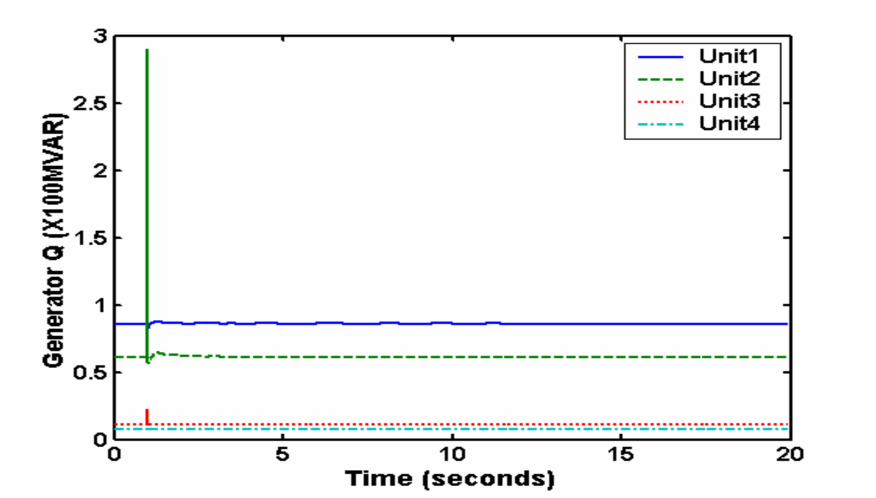


Fig. 4-7. Generator output reactive power

Fig. 4-8 is the oscillation in generator active power output. Dynamics of inter-area power transfer are observed. Of course, the active power of the generator oscillates at the same frequency of that of generator angle that is about 0.6 Hz.

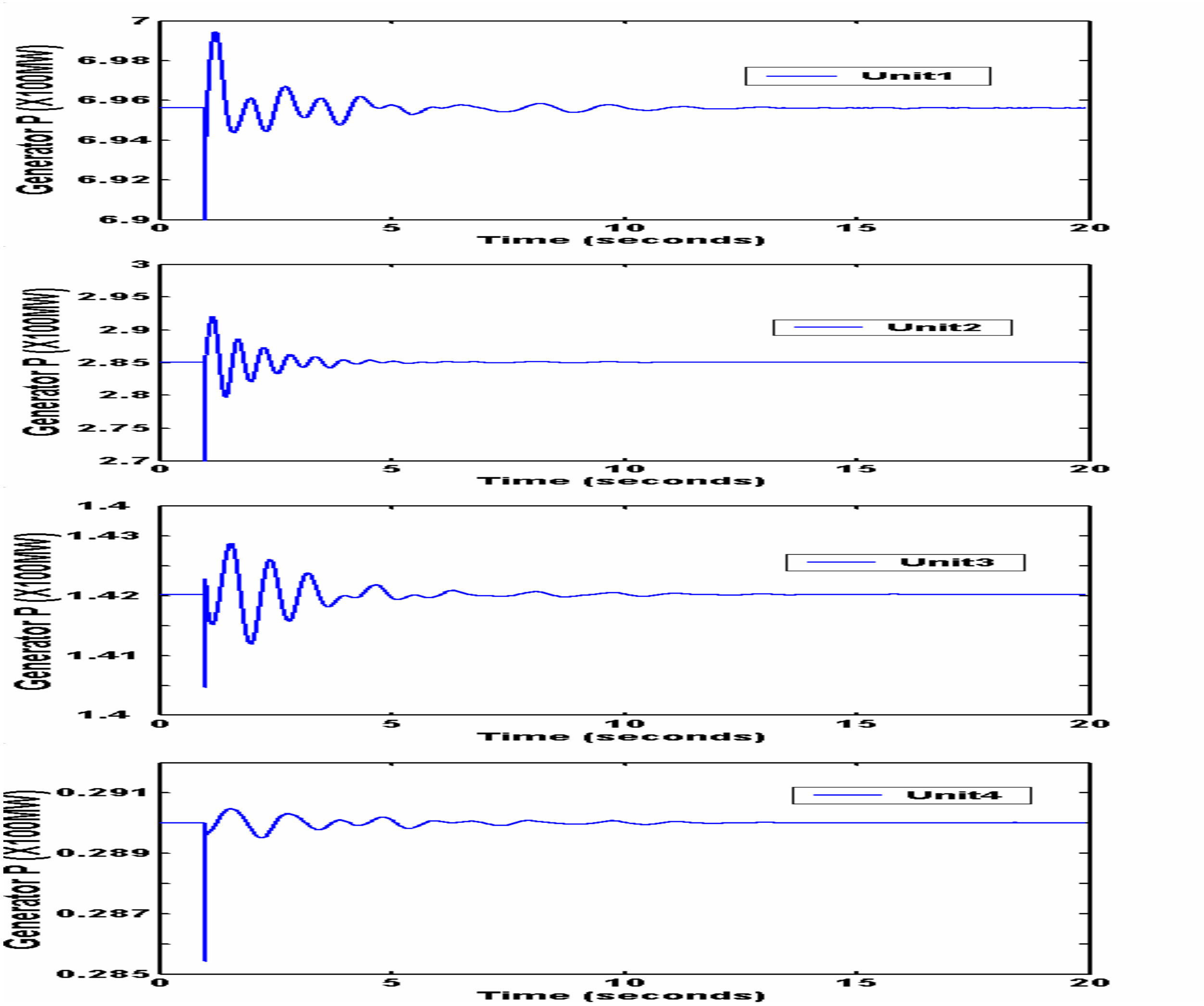


Fig. 4-8. Generator output active power oscillation

Fig. 4-9 is the low frequency oscillation distribution of 17 generators. We chose several generators in each group at the 4 different locations: No.1 and No.2 are located at Cumberland (there are two generators in this area), No.3~No.7 are located at Gallatin, No.8~No.12 are at Kingston, and No.13~No.17 are at Wilson. We can see that generators in Gallatin oscillate more violently than those in the other groups.

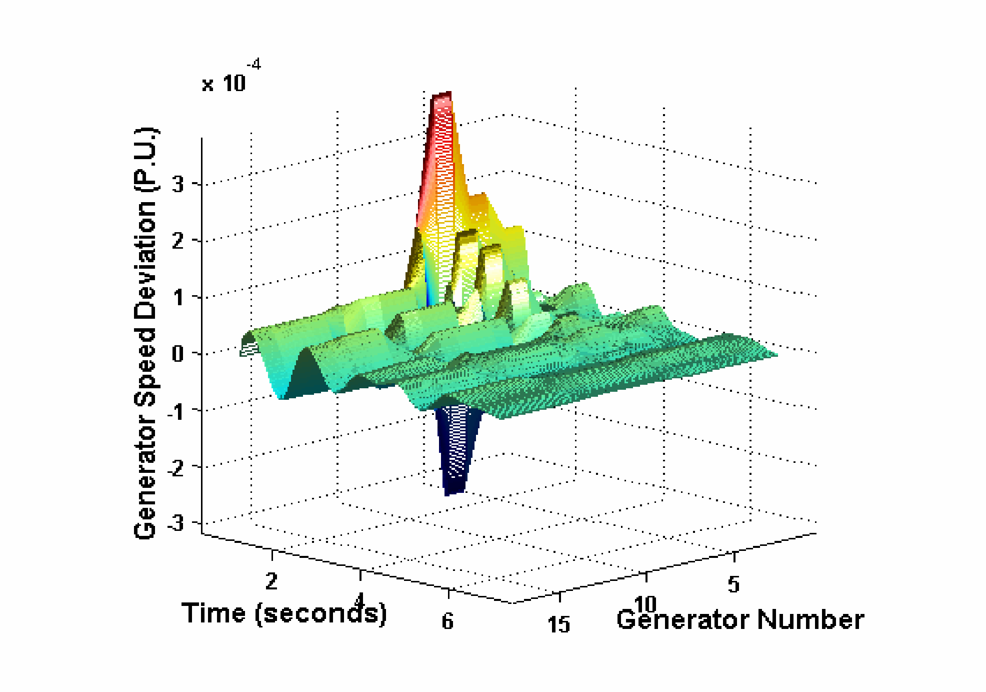


Fig. 4-9. Low frequency oscillation distribution within the research area

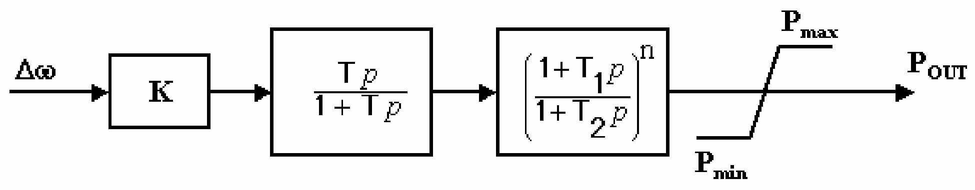
In the past, a great deal of attention has been given to local mode of low frequency oscillations. However, due to the increasing complexity and the need of detailed representation of the entire system, knowledge about the characteristics of inter-area modes and associated control methods are still lacking and warrant further study [58]. The Nashville case is a typical inter-area mode oscillation in a complex bulk power system. As the above figures show, the oscillation mode of Nashville is complex. The oscillation does not happen only between two areas, but among several different areas.

4.3 Power System Low Frequency Oscillation Damping by FACTS/ESS

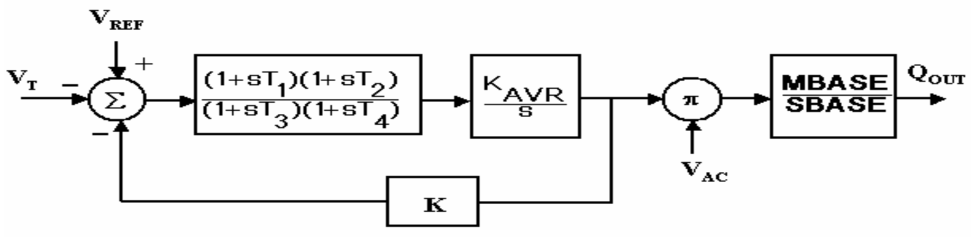
FACTS (without ESS) devices can only utilize and/or redirect the power and energy available on the ac system and, consequently, are limited in the degree of freedom and sustained action to the power grid. Adding ESS to FACTS is able to rapidly inject or absorb active and reactive power and, as a result, will increase the effectiveness of the overall control. Thus, functions such as system stability, transmission capacity, and the overall supply quality provided by power electronic devices, including FACTS devices, can be significantly enhanced by the ability of the ESS to support the actions associated with active power control [71-74].

The configuration of FACTS/ESS in this study consists of three main parts shown in Fig. 3-39: an energy storage system such as battery energy storage system (BESS) or superconducting magnetic energy storage system (SMES), a power converter, and a transformer. The converter produces a three-phase voltage at the secondary winding of the transformer. This voltage can be varied in magnitude and phase with respect to the voltage on the high side of the transformer. The reactive power exchange between the converter and the ac system is controlled by varying the phase of the secondary voltage, and the converter, effectively, a STATCOM that has the added feature of facilitating active power flow between its dc and the ac side.

The control functions of the FACTS/ESS have two parallel independent parts for active power control and reactive power control. The active power control is to control the active power output of FACTS/ESS to suppress the generator rotor oscillation [65]. The reactive power control is to keep the terminal voltage at the reference value [66]. Fig. 4-10 is the control blocks of the two parts. In Fig. 4-10 (a), the K in the first block is the multiplying factor. The second block is the resetting block which makes P_{out} zero when $t \to \infty$, The third block is a phase compensation block which will make P_{out} be synchronous with $\Delta\omega$, in which (T_1, T_2) are time constant and P is integer ranging from 1-3. ρ is Laplas factor. In Fig. 4-10 (b), K_{AVR}, T_1, T_2, T_3, and T_4 are the gain and time constants of the automatic voltage regulator. K is the negative feed back factor. In our case, there is no phase shift with n=0.



(a) Active power control function of FACTS/ESS



(b) Reactive power control function of FACTS/ESS

Fig. 4-10. Control function chart of FACTS/ESS controller

In practice, the control scheme of FACTS/ESS output active power can follow the design of power system stabilizer (PSS) [66] because there is some unclean signal including noise in the real application. So the active power control function of FACTS/ESS can be similar as shown in Fig. 4-11. The signal in this figure could be either the rotor speed deviation or bus frequency deviation. In Fig. 4-11, the first block is the filter function chart. The second and third blocks are the lead or lag compensator function chart that are used for the phase shift compensation.

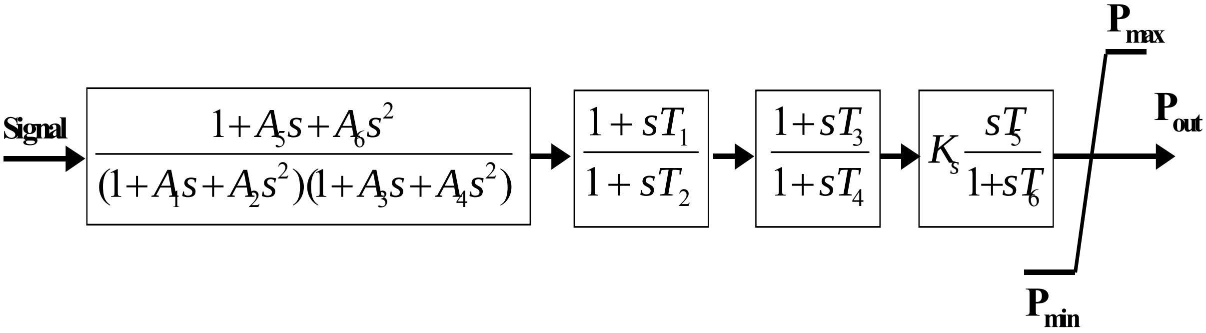
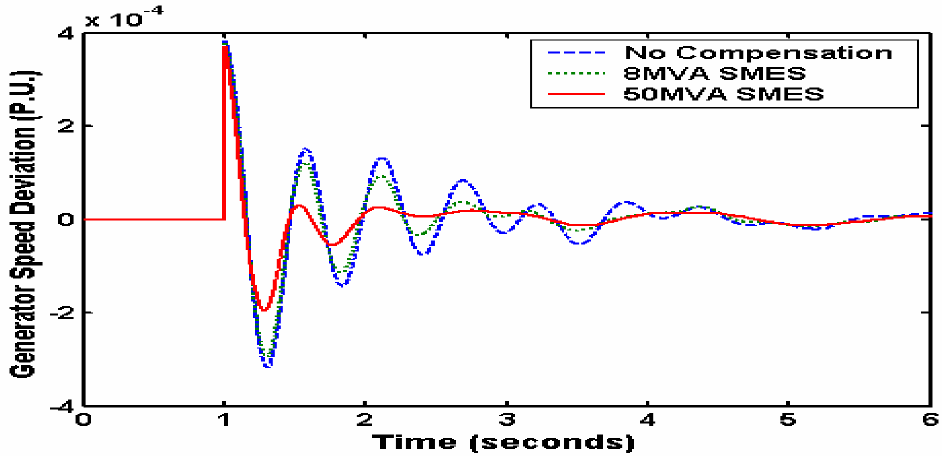


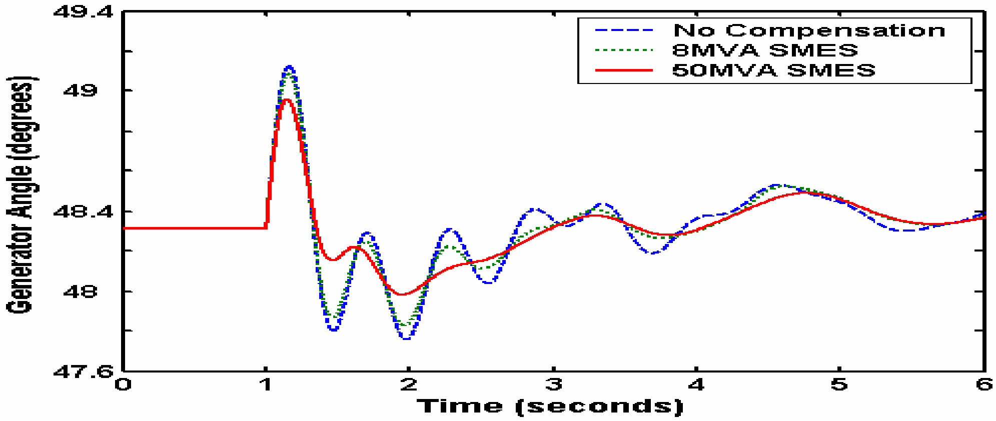
Fig. 4-11 Practical control function chart of FACTS/ESS active power controller

In this study, the FACTS/ESS is located at the Hoeganaes substation near Gallatin (as planned by TVA) to damp the generator rotor oscillation in Gallatin Steam Plant (Unit 2). The control signal $\Delta\omega$ (generator rotor speed deviation of Unit 2 at Gallatin) is used as input to control the active power of ESS that is assumed available from synchronized wide area measurement. The reason to choose it as the input signal is two fold. The generator speed deviation $\Delta\omega$ of Unit 2 at Gallatin is the largest one within the whole system (Fig. 4-9), and the two places are nearby.

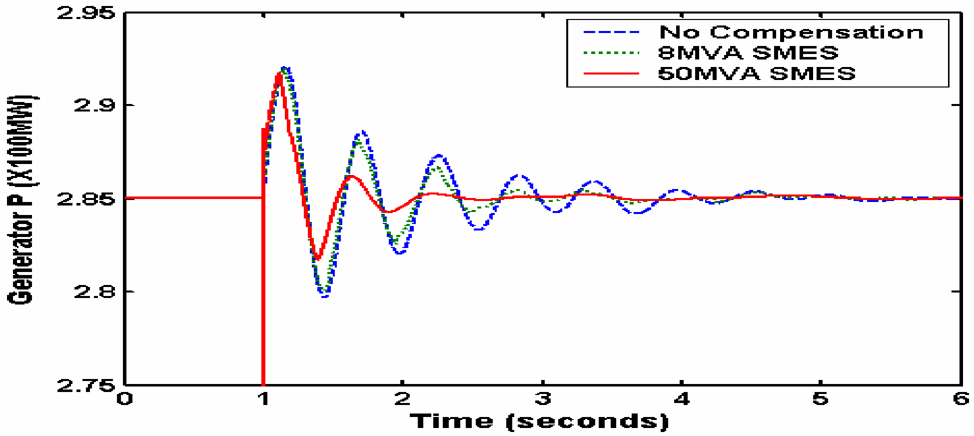
Either the size of 8MVA or 50MVA FACTS/ESS at the Hoeganaes substation is studied in the simulation. Fig. 4-12 to Fig.4-15 are the simulation results with the FACTS/SMES as the example. It should be noted that the FACTS/BESS has the same control effect as the FACTS/SMES in this study based on the same control scheme. Fig. 4-12 is the Unit 2 (at Gallatin) generator rotor speed control effects by different capacity FACTS/SMES, including the generator speed, angle, and active power output. The results show that the 50MVA FACTS/SMES has reasonably good control result. The effect of the 8MVA FACTS/SMES is obviously much less effective then the 50MVA. However, it seems to be working well after 2-3 cycles, when the oscillation magnitude has dropped to a lower level.



(a) Unit 2 (Gallatin) generator rotor speed deviation



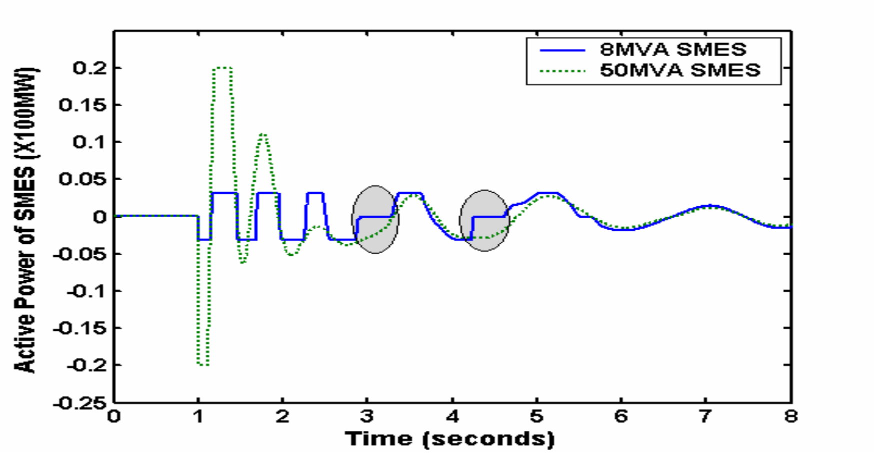
(b) Unit 2 (Gallatin) generator angle



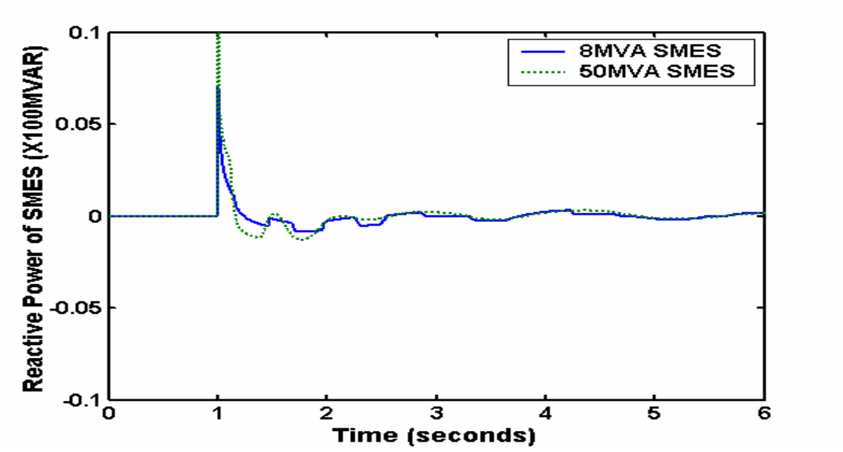
(c) Unit 2 (Gallatin) generator active power output

Fig. 4-12. Unit 2 (at Gallatin) control effects by different capacity FACTS/SMES located at Hoeganaes

Fig. 4-13 is the FACTS/SMES output active and reactive power. We can find that in Fig. 4-13 (a), both the 50MVA and 8MVA FACTS/SMES have the maximum active power output for some periods of time because of the high K control scheme. The output active power of 8MVA FACTS/SMES is zero for some periods of time (shaded areas) because it cannot absorb enough active power with its capacity limit and runs out all the stored energy. The reactive power outputs in Fig. 4-13 (b) are almost the same.



(a) FACTS/SMES output active power



(b) FACTS/ESS output reactive power

Fig. 4-13. FACTS/SMES output active and reactive power

Fig. 4-14 is the relative angle oscillation between Unit 2 (Gallatin) and Unit 4 (Wilson). We can see that the 50MVA FACTS/SMES has better control results than the 8MVA one. The damping result for the Unit 4 generator (at Wilson) is not obvious in Fig. 4-15 because the FACTS/ESS device is located quite some distant from Wilson.

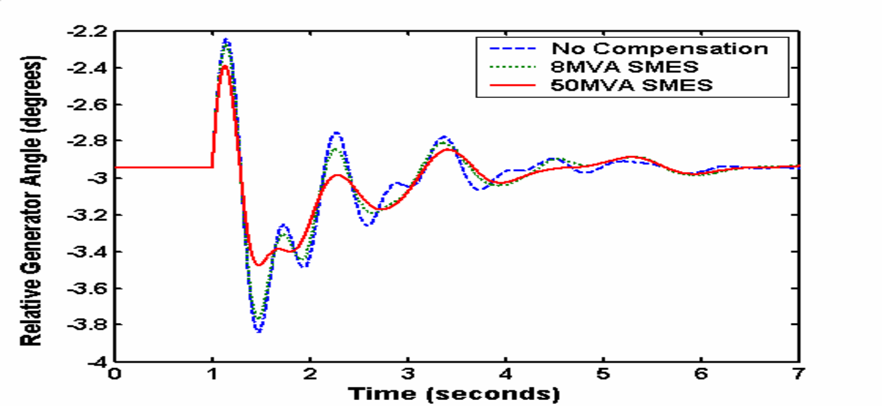
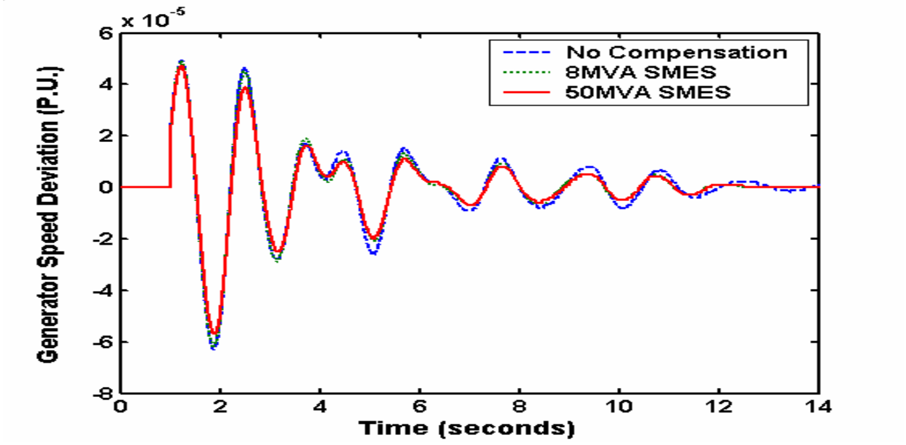
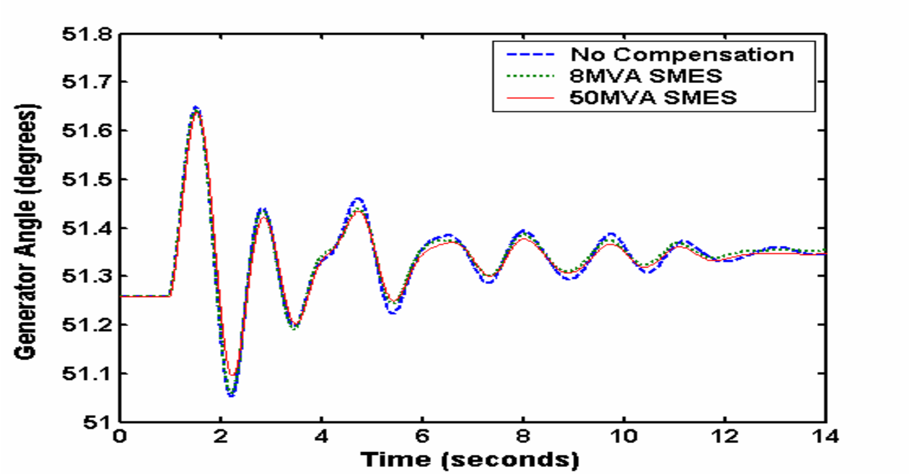


Fig. 4-14. The relative angle oscillation between Unit 2 (Gallatin) and Unit 4 (Wilson)



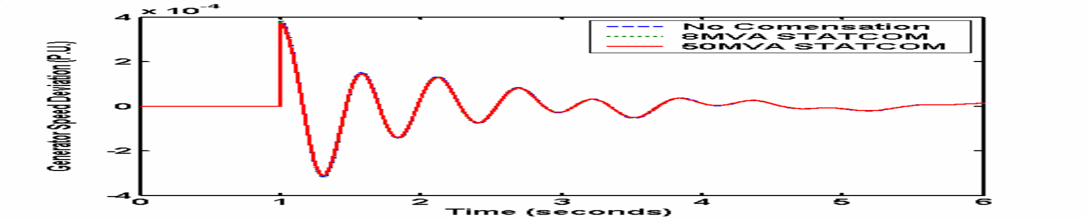
(a) Unit 4 (Wilson) generator speed deviation



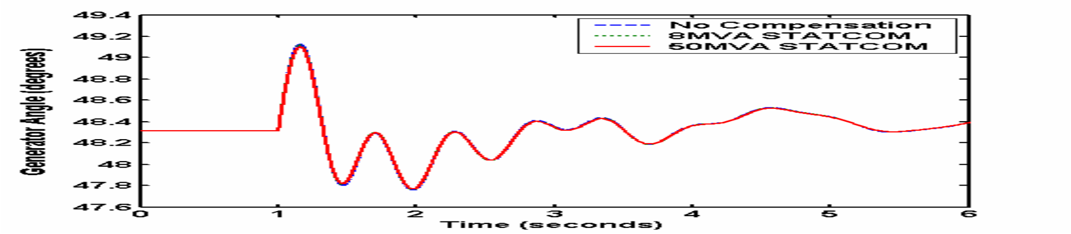
(b) Unit 4 (Wilson) generator angle

Fig. 4-15. Unit 4 (at Wilson) control effects by different capacity FACTS/SMES located at Hoeganaes

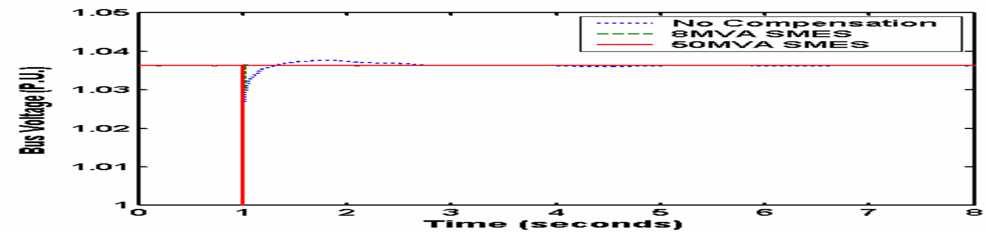
We also look at the STATCOM solution in our study case. 8MVA and 50MVA STATCOM are installed at the same location in Hoeganaes. The control scheme of STATCOM is the same as that used for reactive power control of FACTS/ESS shown in Fig. 4-10 (b). The STATCOM is to control its local terminal voltage during and after the fault. As we see in Fig. 4-17, the local terminal voltage of STATCOM does not have much change soon after the fault. The reactive power output of the STATCOM drops down to almost zero in response to the slight change of the local voltage after fault. For the above reason, STATCOM under this control mode has little effect on damping the oscillation as shown in Fig. 4-16 (a) and (b).



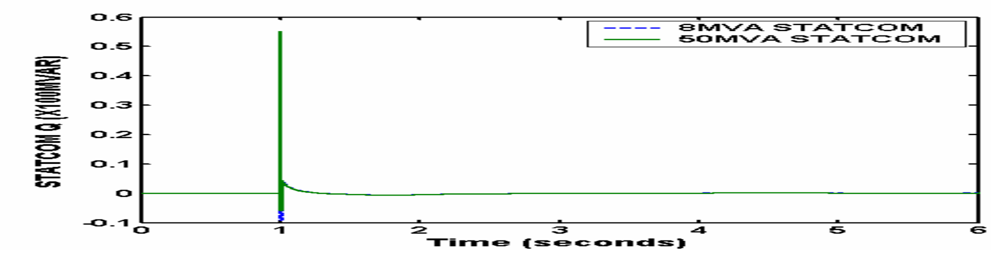
(a) Unit 2 (Gallatin) generator rotor speed



(b) Unit 2 (Gallatin) generator angle



(c) Local terminal bus voltage at Hoeganaes



(d) Reactive power output of different capacity STATCOM

Fig. 4-16. Control effects of different capacity STATCOM

Fig. 4-17 is the control effects of the whole research area by 50MVA FACTS/EES. Comparing with Fig. 4-9, we can see that the oscillation in Group No.2 at Gallatin has been damped to a very low level soon after fault. But the damping results for the generators in the other three areas are not very obvious. That is the limitation of the concentrated control of the FACTS/ESS unit.

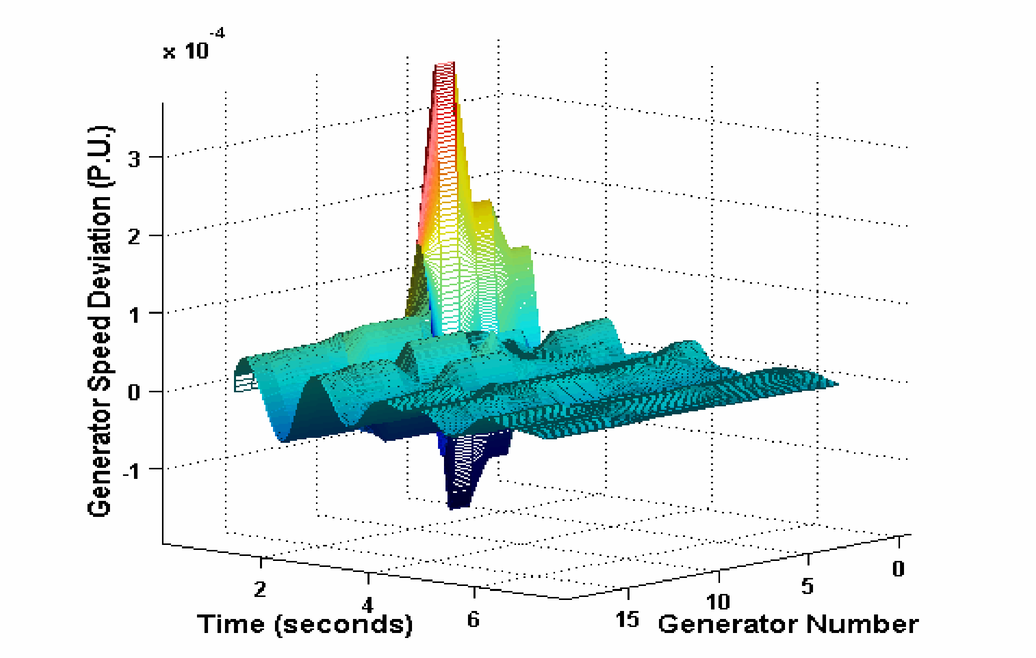


Fig. 4-17. Low frequency oscillation control results by 50MVA FACTS/SMES

4.4 FACTS/ESS Allocation Study

When power system is operated with high power transfer via long transmission lines, unstable phenomena, especially poorly damped electromechanical oscillation will become an important issue. Poorly damped electromechanical oscillation at very low frequencies in the range of 1 Hz or below is of great concern in the power system nowadays. FACTS/ESS devices equipped with proper control system are nowadays also recognized as additional damping resources comparing Power System Stabilizer (PSS). The allocation of FACTS/ESS devices is very important for the control results from the whole system point of view. While FACTS/ESS devices are going to be located into transmission network, an important aspect is that the effectiveness of the damping effect is strongly influenced by their location and control system. As we know, with the optimal placement of FACTS/ESS devices the existing power system could be utilized more effectively.

To investigate the effectiveness of FACTS/ESS on the dynamic behavior of the system it is necessary to introduce an index. However, there is not an effective index for this purpose, in this study, we select the Generator Speed Deviation (GSD) as an index for transient stability evaluation.

In this study, we select the four areas where the 4 group generators are located as the places to install the different capacity FACTS/ESS, to study the control results based on the allocation. In this study, we use the FACTS/SMES as an example because the FACTS/BESS has the same control effects as that of FACTS/SMES. By installing FACTS/ESS in different locations of the power system, and carrying out transient stability simulation for each case, we can select the locations of FACTS/ESS that is most effective from a transient stability viewpoint. Following is the flow chart to show the evaluation approach. Fig. 4-18 shows the flow chart of FACTS/ESS allocation evaluation approach in this study.

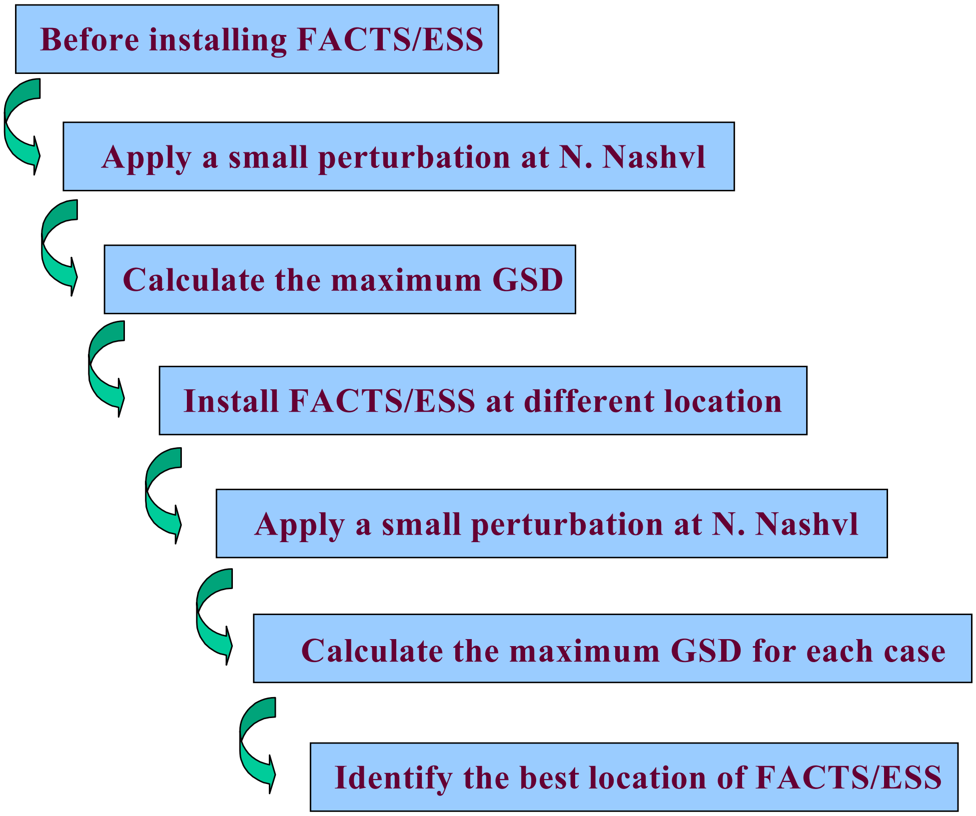


Fig. 4-18. Flow chart of evaluation approach

Fig. 4-19 to Fig. 4-22 show the control results when a 50MVA FACTS/SMES is installed at Cumberland, Gallatin, Kingston and Wilson, respectively. Comparing with Fig. 4-9, we can see that the oscillation in the group where the device is installed has been damped to a very low level. But the control results are not obvious for the generators that locate in the areas where the compensation equipment is not installed. That is the limit of the local control scheme of FACTS/ESS.

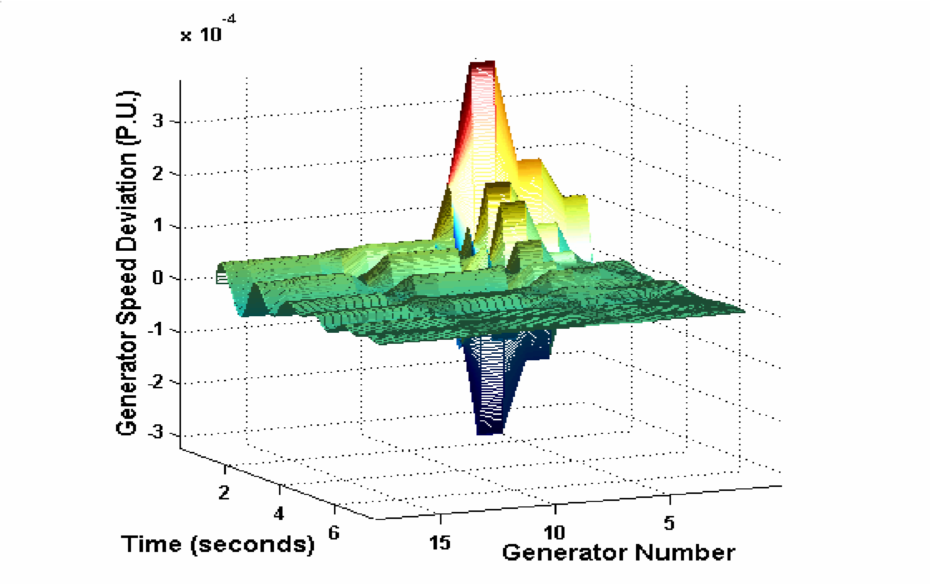


Fig.4-19. Control results when FACTS/ESS is located at Cumberland

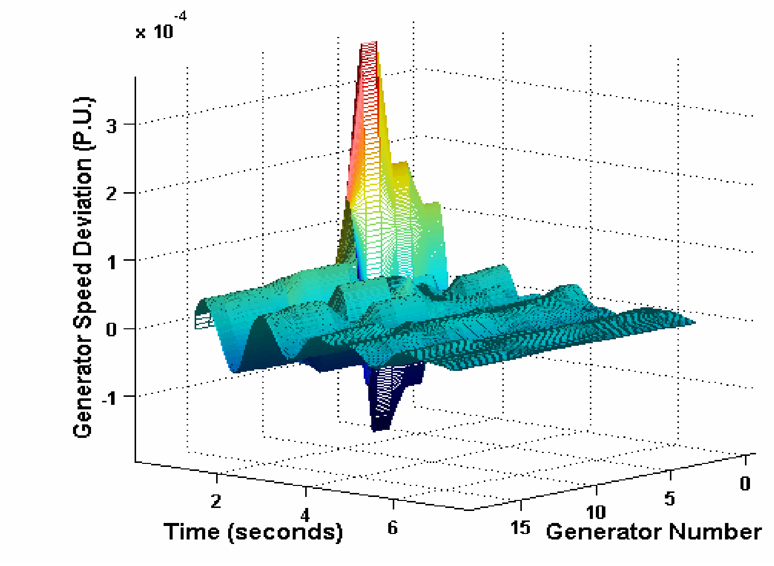


Fig. 4-20. Control results when FACTS/SMES is located at Gallatin

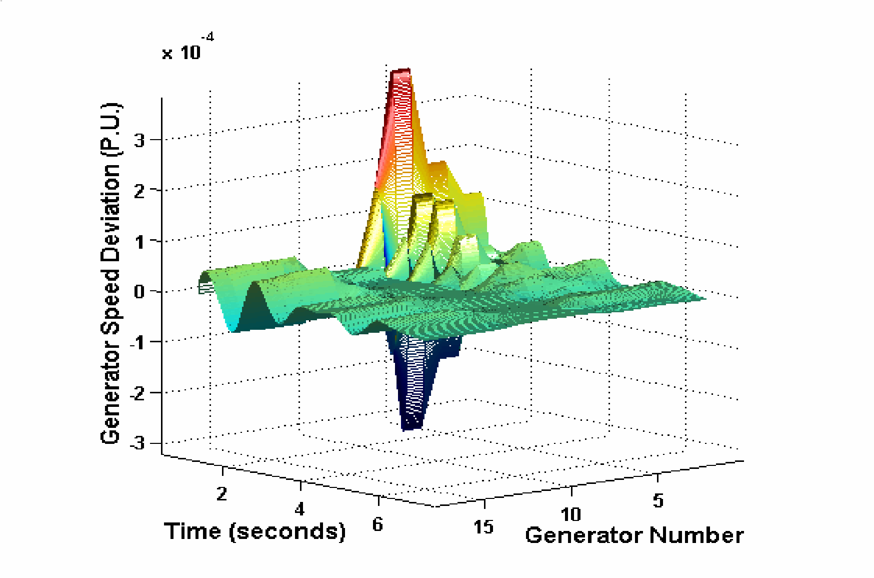


Fig.4-21. Control results when FACTS/ESS is located at Kingston

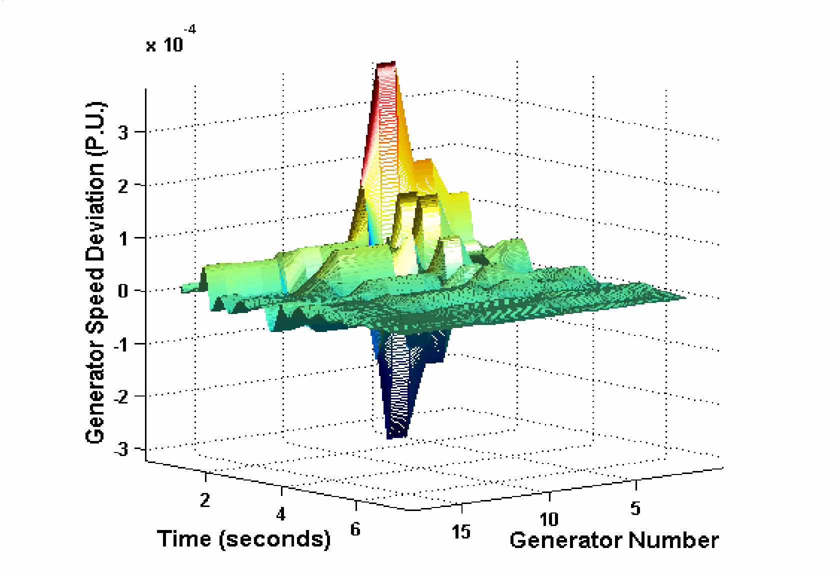


Fig.4-22. Control results when FACTS/ESS is located at Wilson

Table 4-1 to Table 4-4 show the 4 mentioned above generator units rotor speed control results for the different capacity FACTS/SMES when they are installed at different locations. The value in each column is the maximum generator speed deviation (P.U.) when a proper capacity FACTS/SMES is installed at the place named at the top of this column. The value does not consider the first peak value just after the disturbance. For example, the name Cumberland in the second column in Table 4-1 to Table 4-4 means there is a 50MVA FACTS/SMES located at Cumberland.

Table 4-1. Maximum generator rotor speed deviation when there is no compensation

	Maximum Generator Speed Deviation ($\times10^{-4}$ P.U.)
Unit1	0.647
Unit2	3.234
Unit3	0.857
Unit4	0.636

Table 4-2. Comparison of the control results for 50MVA FACTS/ESS

	Maximum Generator Speed Deviation ($\times10^{-4}$ P.U.)			
	Cumberland	Gallatin	Kingston	Wilson
Unit1	0.247	0.555	0.679	0.706
Unit2	3.234	1.39	3.189	3.14
Unit3	0.766	0.798	0.045	0.906
Unit4	0.469	0.555	0.652	0.118

Table 4-3. Comparison of the control results for 24MVA FACTS/ESS

	Maximum Generator Speed Deviation ($\times10^{-4}$ P.U.)			
	Cumberland	Gallatin	Kingston	Wilson
Unit1	0.393	0.604	0.679	0.69
Unit2	3.234	2.29	3.234	3.234
Unit3	0.809	0.841	0.307	0.879
Unit4	0.534	0.598	0.625	0.474

Table 4-4. Comparison of the control results for 8MVA FACTS/ESS

	Maximum Generator Speed Deviation ($x10^{-4}$ P.U.)			
	Cumberland	Gallatin	Kingston	Wilson
Unit1	0.555	0.631	0.658	0.668
Unit2	3.189	2.875	3.144	3.234
Unit3	0.836	0.852	0.679	0.868
Unit4	0.593	0.614	0.62	0.614

Fig. 4-23 to Fig. 4-26 are the figures showing the content in Table 4-1 to Table 4-4. Each figure shows the control results of the four generator units maximum rotor speed deviation (P.U.) when different capacity FACTS/SMES is located at a special place.

Comparing the figures in Fig. 4-23 to Fig. 4-26, only when the different capacity FACTS/SMES is installed at Gallatin, the control results for all the four generator units in the four areas including Gallatin are obvious or positive, which means the generator rotor speed deviation for all the four generator units located in the four areas decreases.

When the equipment is installed at the other three places (Cumberland, Kingston and Wilson), the generator unit rotor speed deviation in the area where the device is not installed will increase sometimes. For example, the maximum rotor speed deviation of Unit 1 and Unit 3 increase when the FACTS/SMES is installed at Wilson shown in Fig. 4-26, even though the local generator speed deviation of unit 4 decreases. Fig. 4-24 has the same phenomenon.

Thus Gallatin is the suitable place to install the FACTS/ESS to damp the low frequency oscillation in the Nashville area in the TVA system. It can offer optimal control results from the whole system point of view.

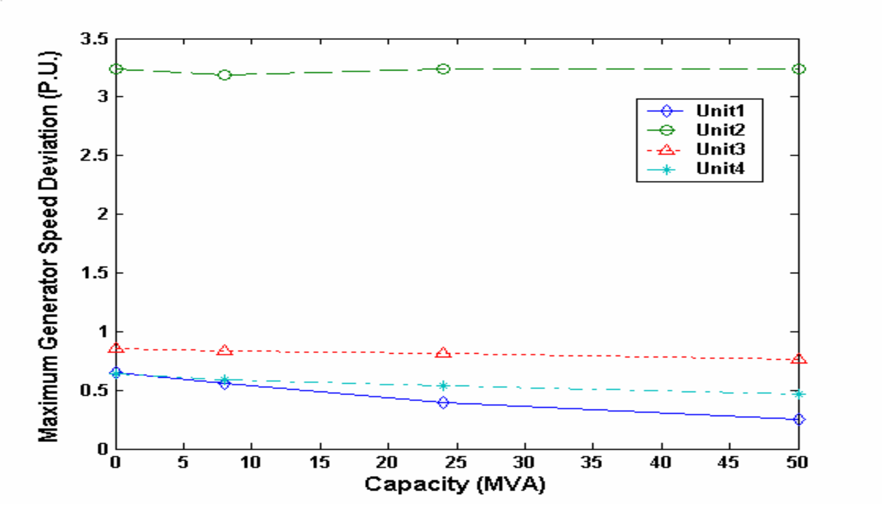


Fig.4-23. Maximum generator unit rotor speed deviation when different capacity FACTS/ESS is installed at Cumberland

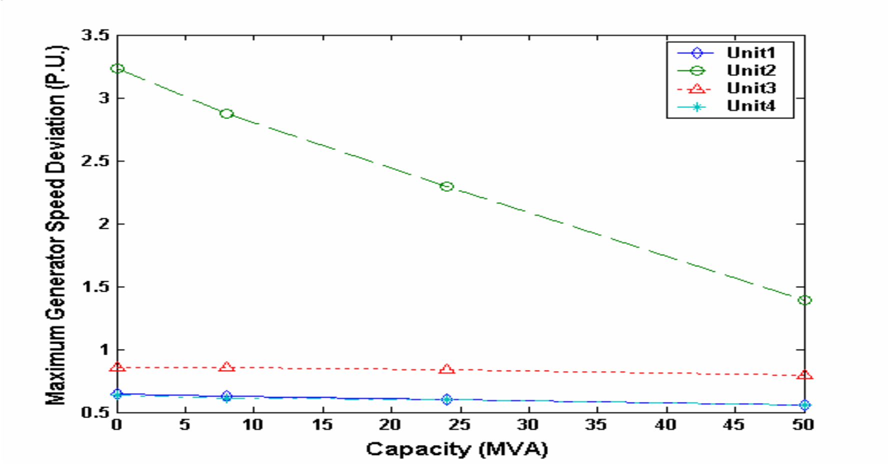


Fig.4-24. Maximum generator unit rotor speed deviation when different capacity FACTS/ESS is installed at Gallatin

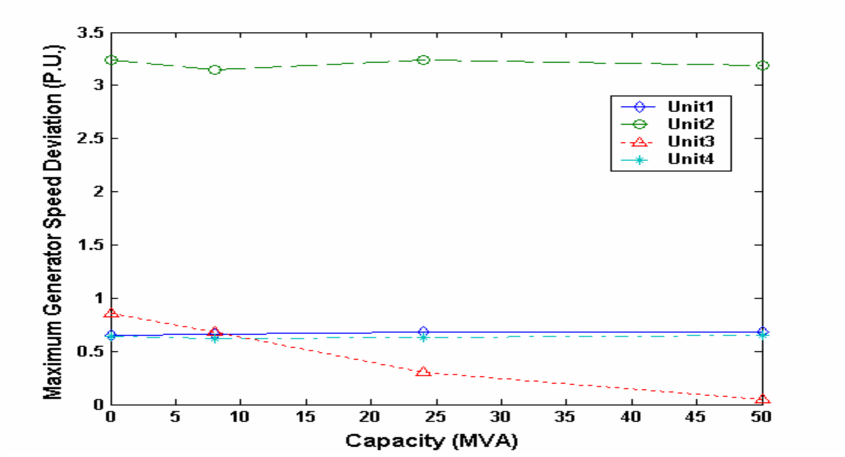


Fig.4-25. Maximum generator unit rotor speed deviation when different capacity FACTS/ESS is installed at Kingston

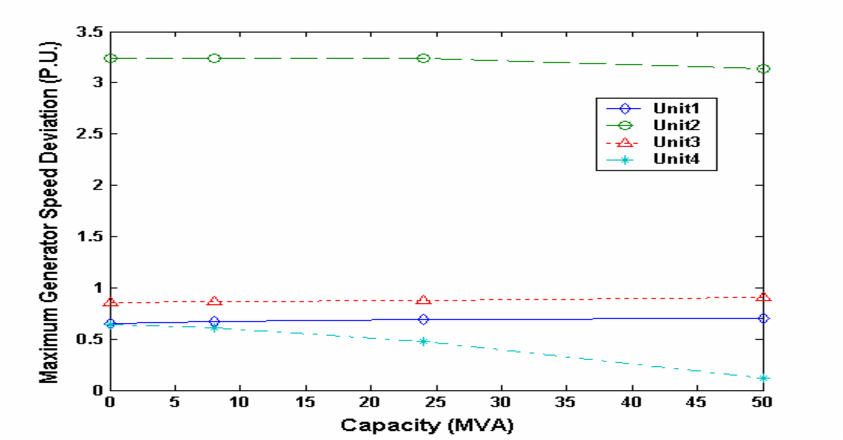


Fig.4-26. Maximum generator unit rotor speed deviation when different capacity FACTS/ESS is installed at Wilson

4.5 Distributed FACTS/ESS Control Scheme

In this study, the distributed FACTS/ESS are installed at the four locations where the generators are located (Cumberland, Gallatin, Kingston and Wilson) shown in Fig. 4-27. The control signal Δω (generator rotor speed deviation of each of the 4 generator units mentioned above) is used as input to control the active power of ESS that is treated as a local control. We have studied three different capacity distributed FACTS/ESS devices, which are 8MVA, 24MVA and 50MVA.

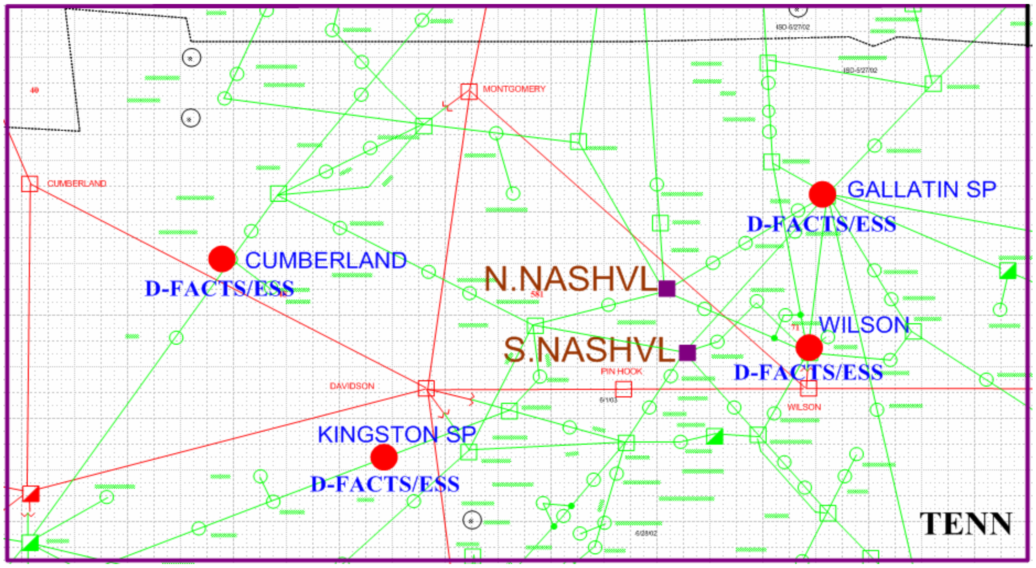
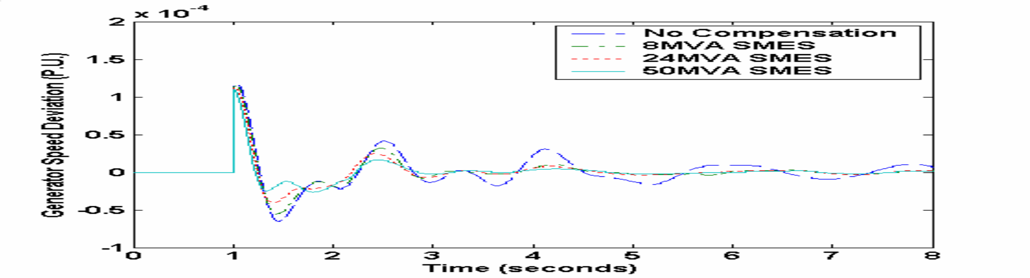
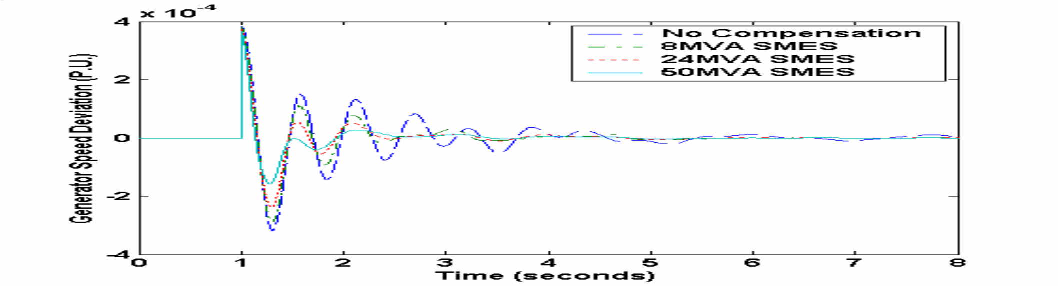


Fig. 4-27. The allocation of the distributed FACTS/ESS

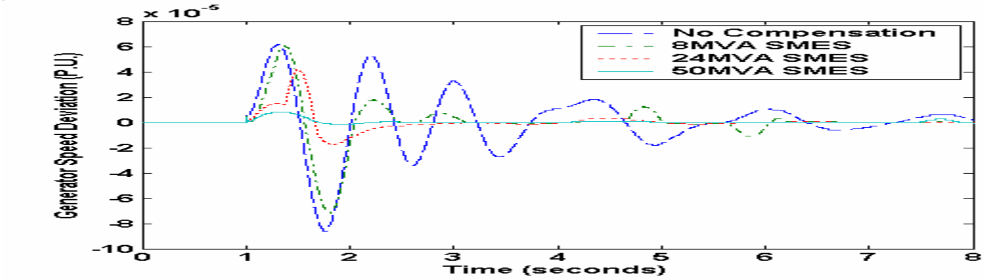
Fig. 4-28 is the control results of the generator rotor speed at the 4 locations for different capacity distributed FACTS/SMES. We can see that even though the control effects of the 4 generator units are similar, obviously higher capacity distributed FACTS/SMES offer better control effects. After 3 cycles, 24MVA SMES has almost the same control effects as those of the 50MVA SMES.



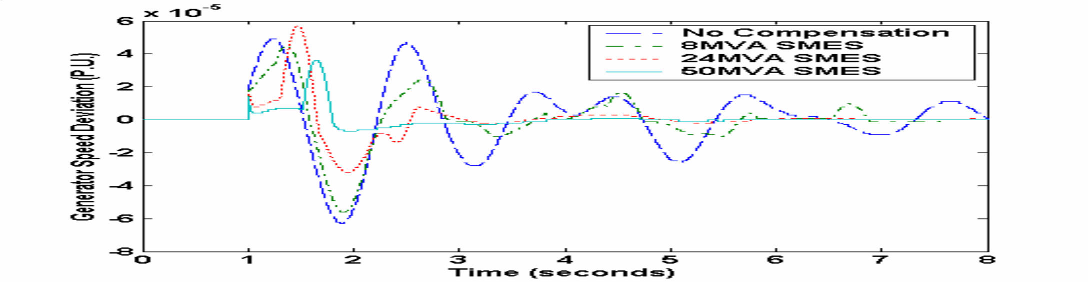
(a) Cumberland



(b) Gallatin



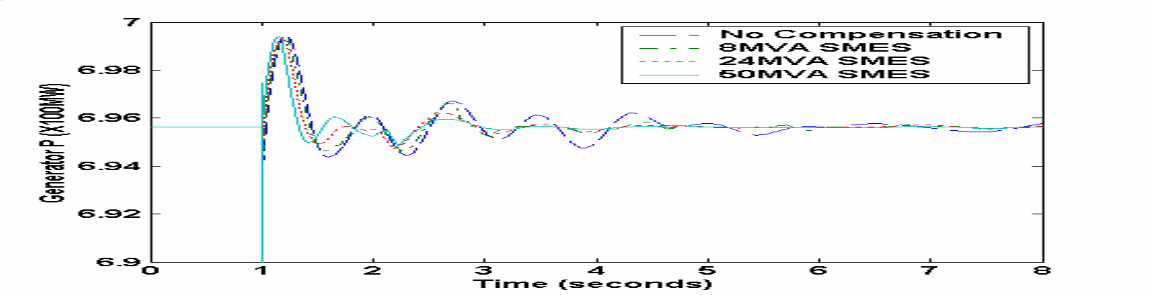
(c) Kingston



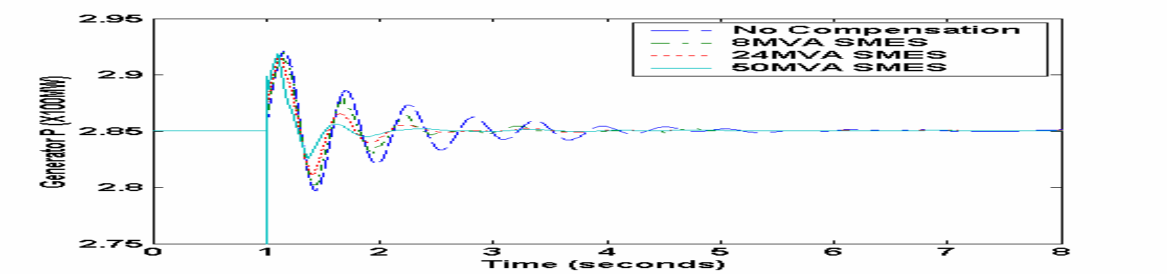
(d) Wilson

Fig. 4-28. Generator rotor speed control results

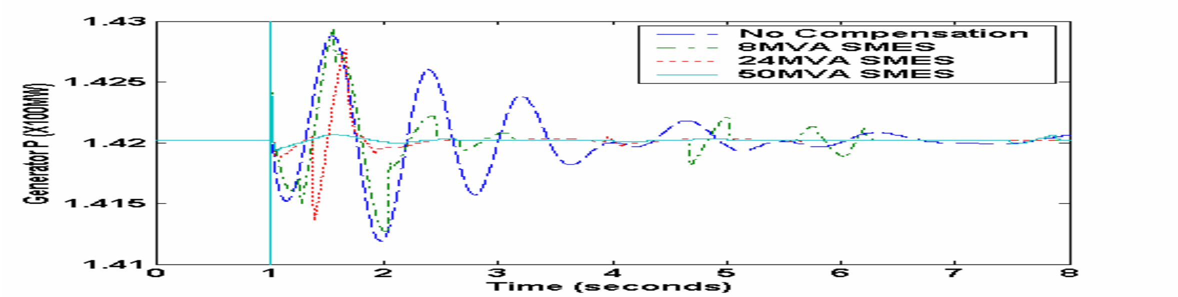
Fig. 4-29 is the control result of the generator active power output. It shows that there is almost no generator active power output oscillation after 2 cycles for the 24MVA and 50MVA FACTS/SMES. There is a little such oscillation for the 8MVA distributed FACTS/SMES because of its less and limited capacity.



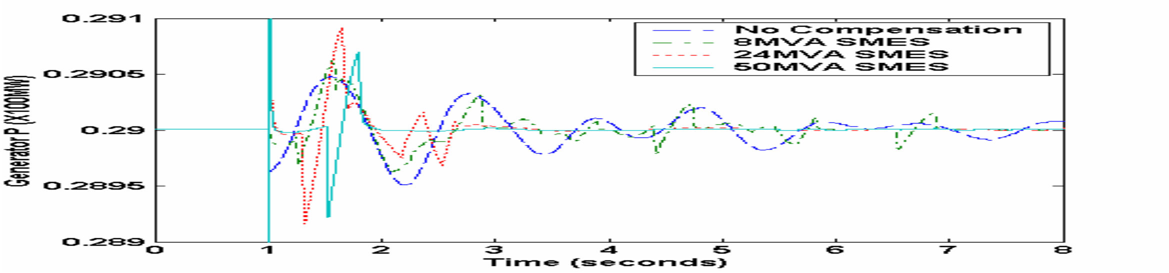
(a) Cumberland



(b) Gallatin



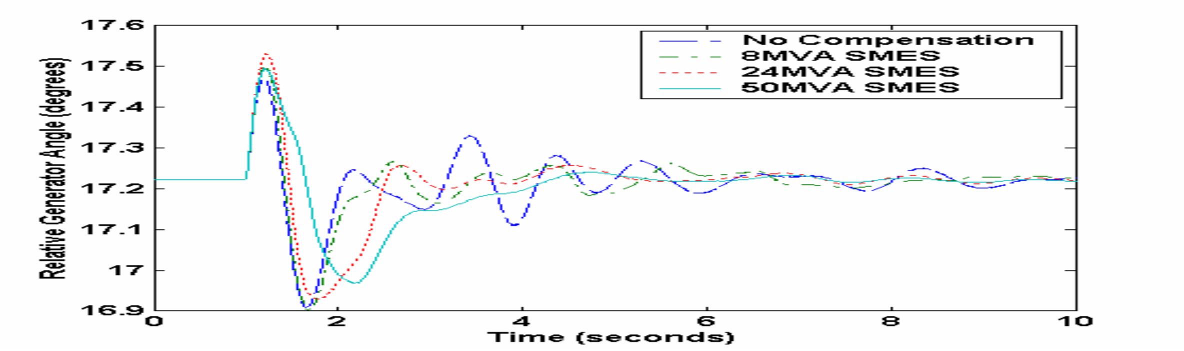
(c) Kingston



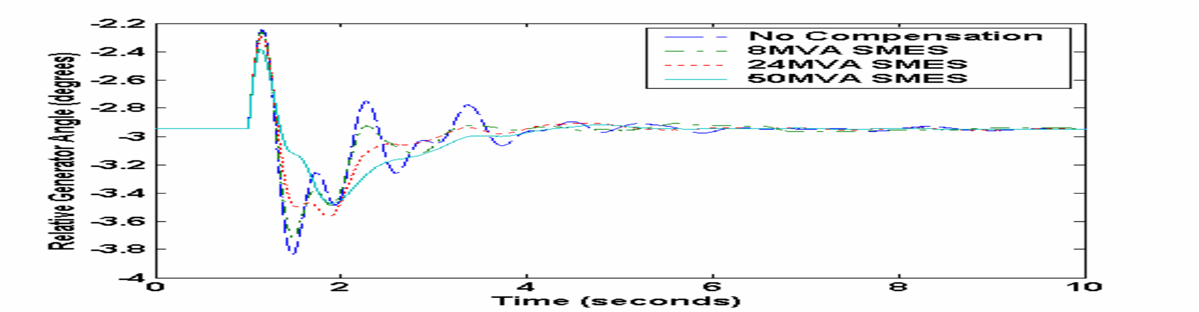
(d) Wilson

Fig. 4-29. Generator active power output

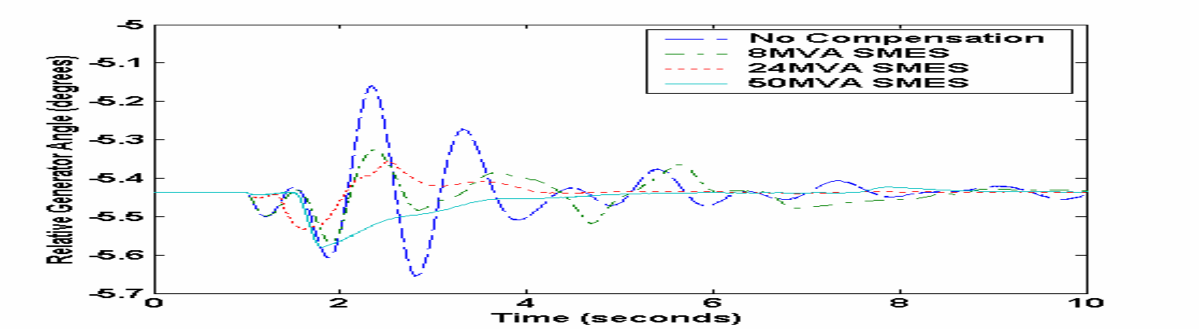
Fig. 4-30 is the control result of the relative generator angle of the other 3 generator units at Cumberland, Kingston and Wilson against unit 4 located at Wilson. The results show that distributed FACTS/SMES can damp the power transfer oscillation effectively, especially when higher capacity devices are used. That will reduce the possibilities of losing stability of the whole system.



(a) Unit 1 against Unit 4



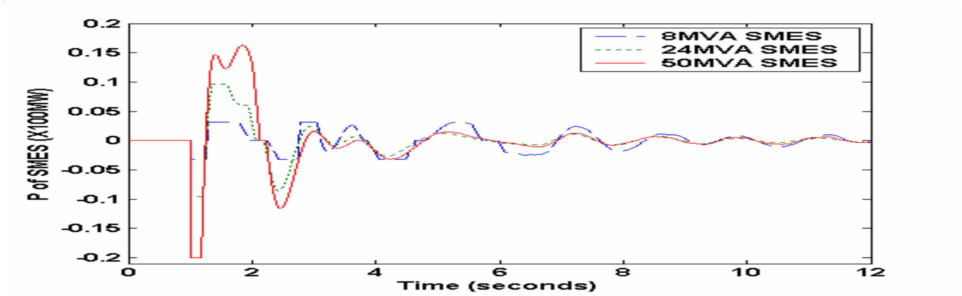
(b) Unit 2 against Unit 4



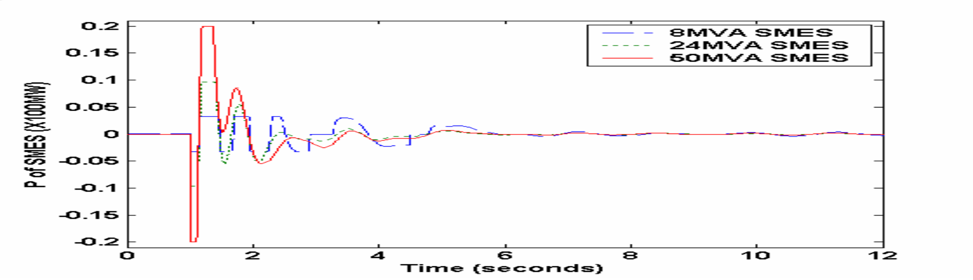
(c) Unit 3 against Unit 4

Fig. 4-30. Relative generator angle of unit 1, unit 2 and unit 3 against unit 4

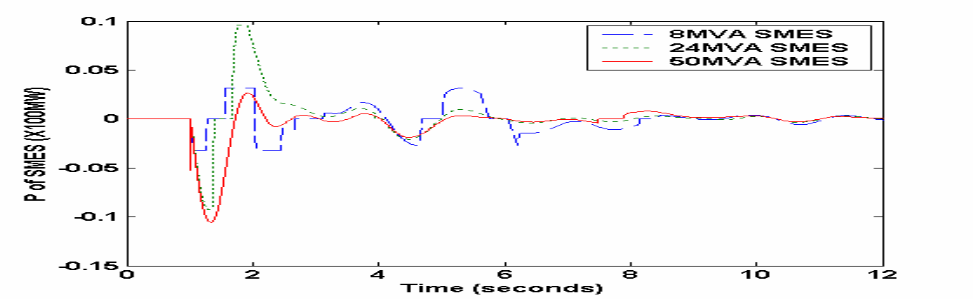
Fig. 4-31 is the D-FACTS/SMES active power output. All the 8MVA, 24MVA and 50MVA D-FACTS/SMES have the maximum active power output for some periods of time because of the high K control scheme. The simulation results show that the distributed FACTS/SMES can suppress the low frequency oscillation in all four locations, which is superior to that of the concentrated local control of such devices.



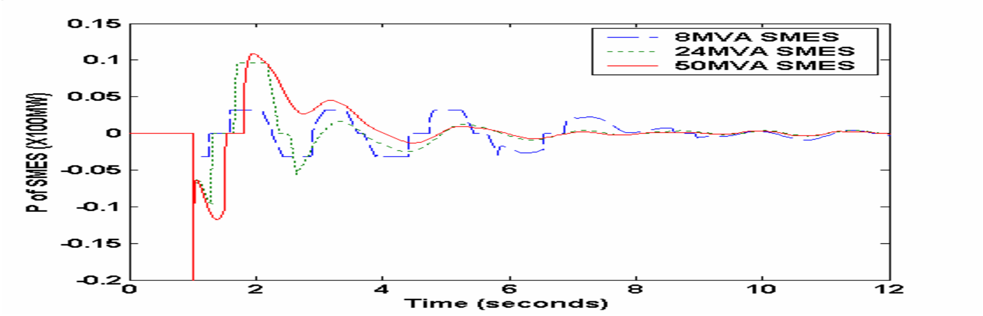
(a) Cumberland



(b) Gallatin



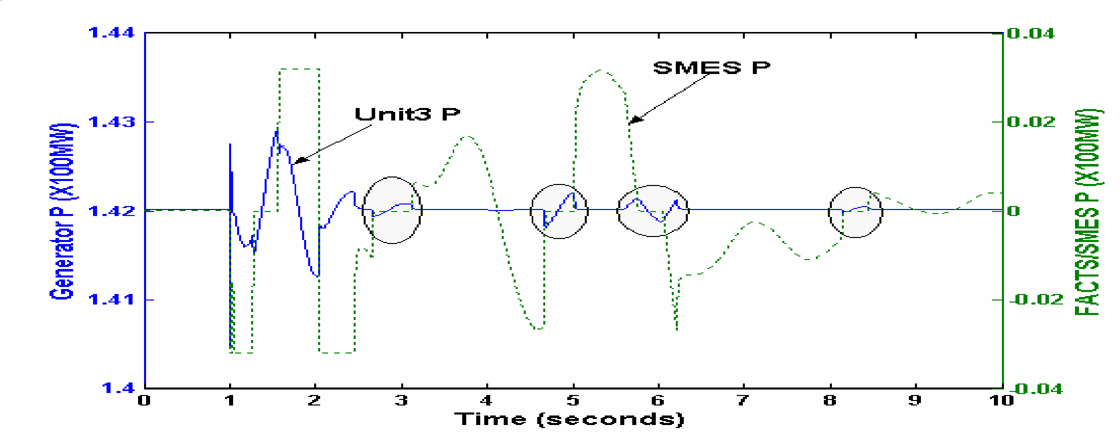
(c) Kingston



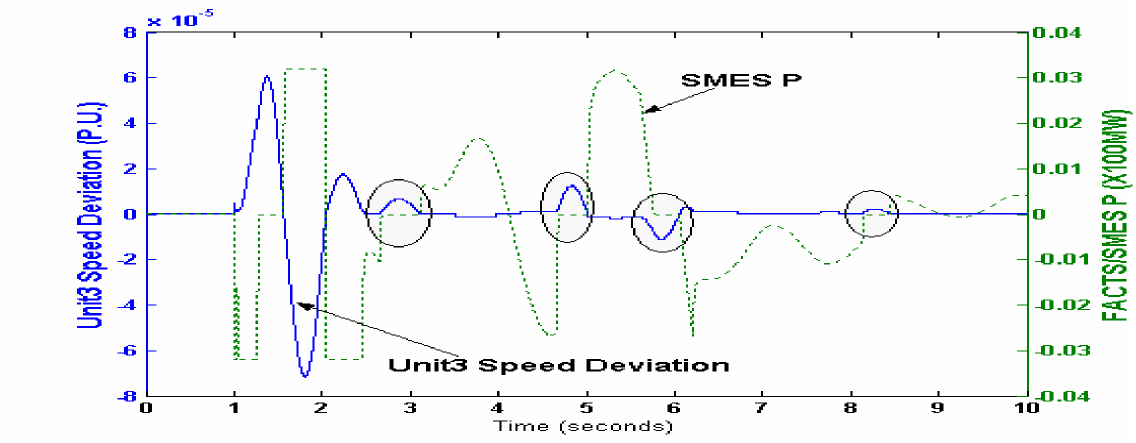
(d) Wilson

Fig. 4-31. Active power output of FACTS/SMES

In Fig. 4-31, the output active power of 8MVA D-FACTS/SMES is zero for some periods of time because it cannot absorb more active energy for its capacity limit and runs out all its stored energy, which is shown in detail in Fig. 4-32. In Fig. 4-32 (a), the active power output of 8MVA D- FACTS/SMES is zero in the shaded area because of its capacity limit. That will have effects on its control results. In Fig. 4-32 (a), when active power output of 8MVA FACTS/SMES is zero, it loses the ability to improve generator (Unit 3 at Kingston) active power output, which means the generator output has some small oscillations. The same is shown for the control of generator rotor speed shown in Fig. 4-32 (b).



(a) Unit 3 (Kingston) generator active power output for 8MVA SMES.



(b) Unit 3 speed deviation for 8MVA SMES.

Fig. 4-32. The limited capacity effects of the 8MVA SMES

Table 4-5 is the comparison of the control results of the above different capacity distributed FACTS/ESS. The value does not consider the first peak value just after the disturbance. Table 4-

5 shows that the better control results will be achieved when using the larger capacity distributed FACTS/ESS.

Table 4-5. Comparison of the control results

	Maximum Generator Speed Deviation (x10^{-4} P.U.)			
	No Compensation	8MVA Device	24MVA Device	50MVA Device
Unit 1	0.647	0.555	0.409	0.264
Unit 2	3.234	2.875	2.38	1.57
Unit 3	0.857	0.717	0.183	0.02
Unit 4	0.639	0.566	0.323	0.064

Fig. 4-33 shows the content in Table 4-5. We can see that the maximum generator rotor speed deviation for the 4 units decreases when the capacity of FACTS/ESS increases.

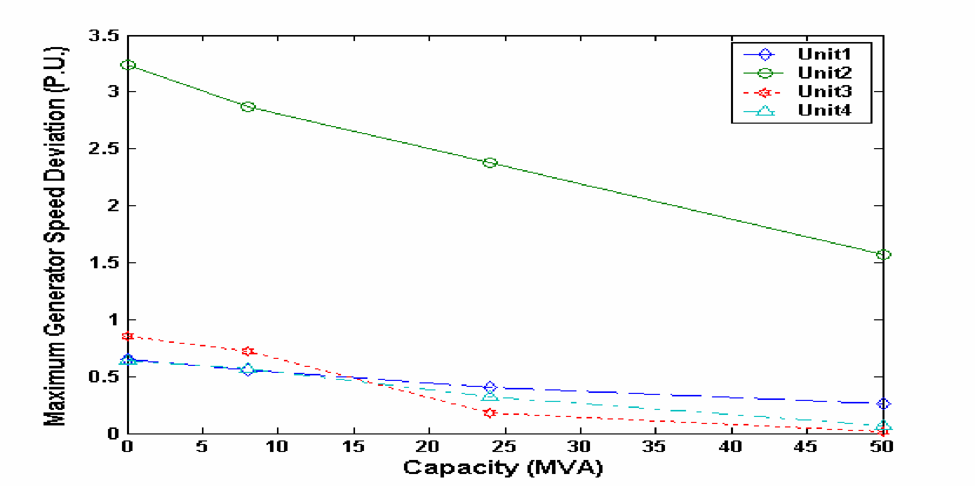


Fig. 4-33. Maximum generator unit speed deviation for different capacity distributed FACTS/ESS

Fig. 4-34 is the control effect of the whole area by 50MVA distributed FACTS/SMES. Comparing with Fig. 4-9, we can see that the control result is very good. There is almost no oscillation after 2~3 cycles in the whole area. That is the advantage of the distributed compensation using D-FACTS/SMES devices.

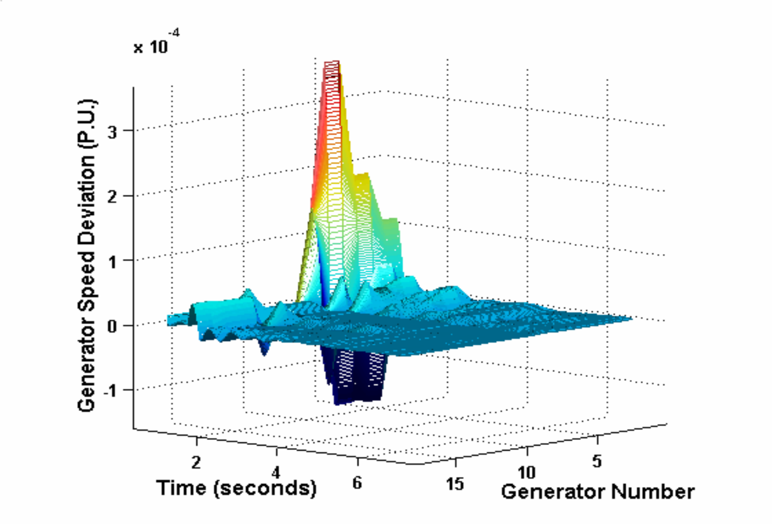


Fig. 4-34. Low frequency oscillation control results by a 50MVA FACTS/SMES

As we seen from the previous FACTS/ESS control results, the concentrated allocation FACTS/ESS device cannot damp low frequency oscillation in all four areas generator groups. It can only successfully damp local low frequency oscillations. Table 4-6 is the comparison of the control results for the above tow different control schemes listing the maximum generator speed deviation of the 4 generator units from each area for (a) no compensation, (b) 50MVA concentrated FACTS/ESS located at Gallatin and (c) distributed compensation by 4 one of the 12.5 MVA devices located in 4 areas. Even though the concentrated FACTS/ESS control scheme can damp the local low frequency oscillation to a lower level than that of the distributed one, but the distributed FACTS/ESS control has a better control results from the power of view of wide-area control results.

Table 4-6 Comparison of the control results

	Maximum Generator Speed Deviation (x10^{-4} P.U.)		
	No Compensation	Concentrated FACTS/ESS	Distributed FACTS/ESS
Unit 1	0.647	0.56	0.512
Unit 2	3.234	1.93	2.74
Unit 3	0.857	0.809	0.512
Unit 4	0.639	0.566	0.485

4.6 Summary

The author studied the inter-area mode power system low frequency oscillations by analyzing the low frequency oscillation phenomena in the Nashville area of the TVA system. There are 4 dynamic groups of generators that oscillate against each other in other groups. The author designed a FACTS/ESS controller and used remote generator speed deviation as one of the control inputs to damp the low frequency oscillations in the Nashville area. While the active power of FACTS/ESS is controlled to damp the Gallatin local low frequency oscillation, the reactive power of FACTS/ESS is controlled to keep the local voltage at a constant level.

The study results show that FACTS/ESS can be used to damp the low frequency oscillations. The damping in the generator where the FACTS/ESS is installed is very effective. The damping effects in the other generators located at some distance away from the FACTS/ESS unit are very limited. In our study, the 50MVA FACTS/ESS has the best control effects due to its relative large size. The effect of the 8MVA unit is only more observable about 2-3 cycles after the fault. The 8 MVA unit could obviously help shorten the oscillation. When the 50 MVA unit was divided into 4 equal parts the results show the “distributed” scheme has better overall effect.

Allocation study was also conducted to find the optimal location to install the concentrated FACTS/ESS to solve this inter-area mode low frequency oscillation within large area. The best location was proposed.

For comparison, the author also studied the effect of STATCOM without energy storage device. The results show that STATCOM has almost no effect in damping the low frequency oscillations in this particular case. This does not imply that STATCOM cannot be used to damp the low frequency oscillation in general.

Distributed FACTS/ESS option is also studied in this chapter. The author designed the distributed FACTS/ESS controller and use local generator speed deviation as one of the inputs to damp the low frequency oscillation in Nashville area. One distributed FACTS/ESS is installed at each location where one-group generators are located. The active and reactive power controls of D-FACTS/ESS are independent. The active power of D-FACTS/ESS is controlled to damp the local low frequency oscillation. Reactive power of D-FACTS/ESS is controlled to keep the local voltage at a standard level. For comparison, the author studied the control effects of different capacity distributed FACTS/ESS. The results show that better control result will be achieved when adequate capacity devices are used.

Chapter 5. Coordination of UFLS and UFGC by Application of FACTS/ESS

5.1 Introduction

One of the most undesirable conditions for power system operation is the loss of generator units or transmission lines causing big power-load unbalance. This kind of unbalance will cause the drop of power system frequency from its steady state. If not properly counteracted it can lead to major stability problems [80]. The typical protection scheme for such conditions is under frequency load shedding (UFLS) to stop the frequency drop after generation-load unbalance happens. UFLS is a final action to mitigate the severe consequences [81].

Load shedding is accomplished by frequency sensitive relays. The relays measure the frequency and rate-of-change of frequency to disconnect load. UFLS is usually implemented in several stages with each stage to shed a particular amount of load at its frequency setting point [82]. In most severe generation-load unbalance conditions, the frequency drops so quickly that the governor cannot fully activate spinning reserve. Most of the time, UFLS serves as a tool to prevent the system collapse before governor can fully activate spinning reserve quickly enough to restore the system to its normal operating frequency. This may results in over-shedding. Generally, the underfreqeuncy governor control (UFGC) cannot help to prevent system from collapse by activate system reserve quickly because of its inertia. UFLS happens before UFGC has the time to take full action. Unfortunately, no method exists to coordinate these two functions before the study in this dissertation [83].

As an example of energy storage system (ESS) technology, D-SMES system has the advantages in both energy storage ability and flexibility of its power electronics interface. D-SMES has been employed due to its capability to work as active and reactive power generation and absorption systems. Besides the task of voltage control, it may also be applied to improve the transmission capability and system stability [67, 68]. The application of D-SMES can provide the ride through to coordinate the UFLS and UFGC. It can help to fully activate the system spinning reserve, which can prevent over shedding.

In this study, the author analyzed the coordination of UFLS and UFGC by D-SMES application. The reason for using D-SMES rather than a concentrated SMES is to coordinate the UFGC locally. The application of D-SMES is to support the active energy to stop the quick drop of system frequency and wait for the full performance of UFGC which can fully activate the system spinning reserve, resulting in avoiding over shedding.

5.2 Theory of Under Frequency Governor Control

During an emergency underfrequency condition of a power system, localized under frequency governor control should override controls based on economic dispatch. This will help prevent the system from collapse by activating spinning reserves more quickly.

The frequency of a generator is maintained by its governor. The control variable for the governor, the load reference set point, is normally obtained from an automatic generation control (AGC) system based on economic dispatch. During an emergency underfrequency situation, economics should not determine governor action and supplementary local control should be initiated.

The amount of spinning reserve (the total amount of generation available from all synchronized units minus the present load) of a system is chosen so that the loss of one or more generating units does not cause too far drop in system frequency. If a severe underfrequency condition occurs, this spinning reserve should be activated as quickly as possible in an attempt to prevent the system from collapse.

After recognizing the need of UFGC, the load reference set points of all governors should be set to their maximum value. This will force generation output to increase at the fastest possible rate. If sufficient spinning reserve generation is not available, power should be imported from a neighboring system. Importing of power should only take place at the frequency restoration stage. In the case of islanding, priority should be given to the island with the largest load. Fig. 5-1 shows the frequency range for each system frequency controllers in power system. Power system frequency is tightly controlled under normal and non-normal conditions by the coordination of all the associated controllers [92].

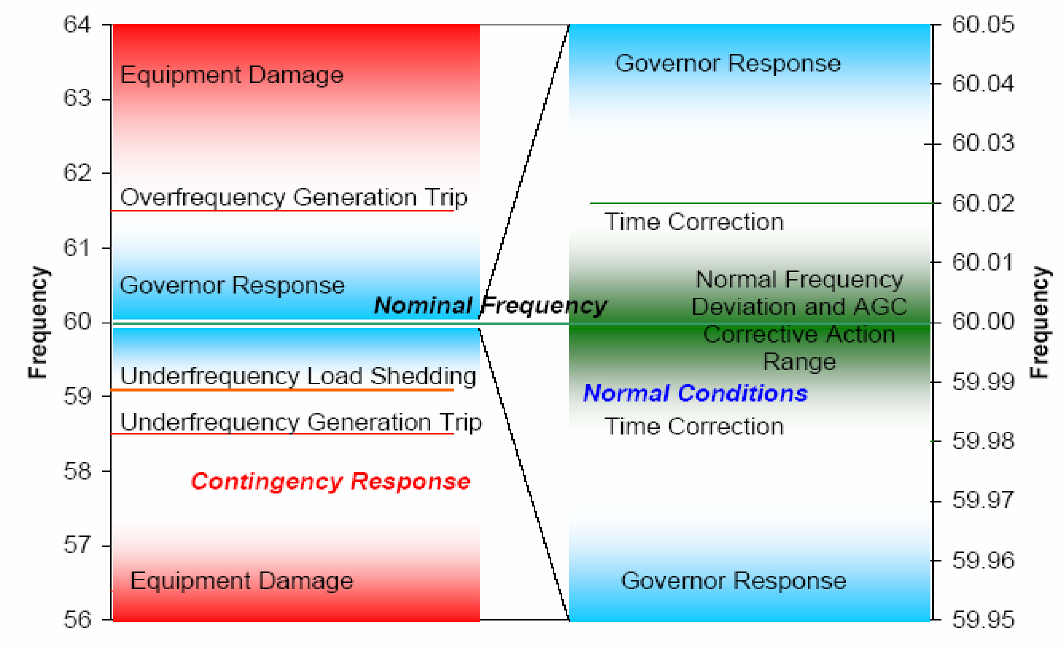


Fig. 5-1. Frequency is tightly controlled under normal conditions and coordinated under all conditions [92]

In PSS/E, the turbine-governor models are designed to give representations of the effects of power plants on power system stability. They are not intended to use in studies of the detailed behavior of individual plants. A functional diagram of the representation used and its relationship to the generator is shown below in Fig. 5-2 [66].

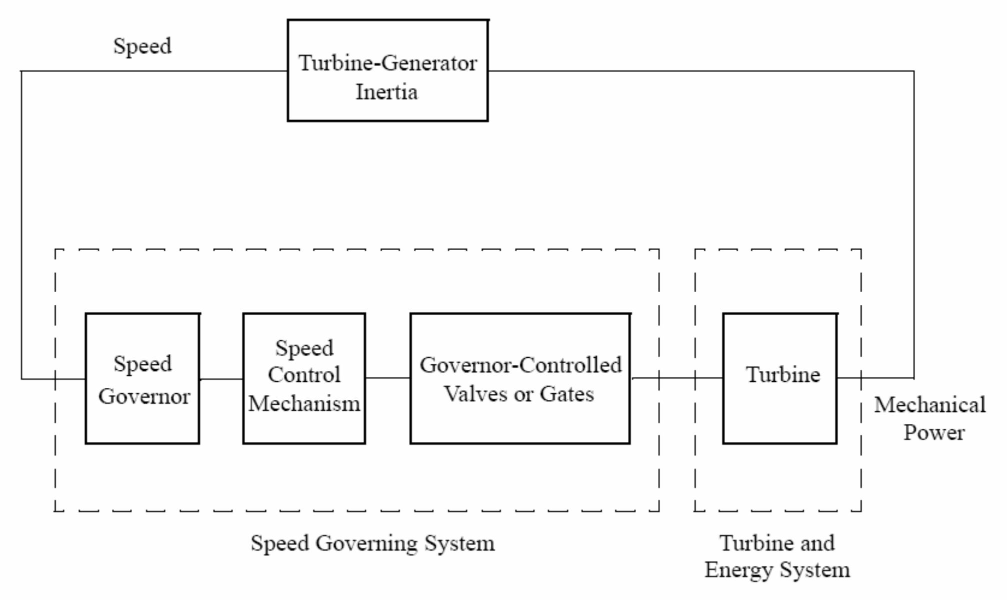


Fig. 5-2. Speed governor and turbine in relationship to generator [66]

Because of the wide variety in the details of individual turbine controls, the PSS/E models do not attempt to give a high degree of exactness for any given plant; rather they represent the principal effects inherent in conventional steam turbine, gas turbine, nuclear, and hydro plants.

5.3 Under Frequency Load Shedding Study

5.3.1 Theory of UFLS

When load and supply for a given portion of power systems are unequal, or not distributed equally, any type of a sudden generation or transmission deficiency may cause cascading outages. Only if enough load is shed from a system, in which the load significantly exceeds generation, the whole system can survive. The generation deficiency most often results from the loss of a major transmission line or transformer, which was transferring large amount of power. Frequency is a reliable indicator that such a deficiency condition exists on the power system [84, 85].

Underfrequency load shedding is performed in order to minimize the risk of a further uncontrolled system separation, loss of generation, or system shutdown. If sufficient load is shed to preserve interconnections and keep generators on line, the system can be restored rapidly. If the system collapses, a prolonged outage will result.

Underfrequency load shedding plans are based on studies of a system's dynamic performance, given the greatest probable imbalance between load and generation. Plans should be coordinated between interconnected power systems as well as with underfrequency isolation of generating units, tripping of shunt capacitors, and other automatic actions which occur in the system under abnormal frequency, voltage, or power flow conditions [86, 87].

Underfrequency relaying can also be utilized to sense disturbances and separate power systems by opening system ties. This requires close coordination between interconnected power systems. Similar relaying can be utilized to separate non-utility generation from the utility power system during system disturbances, but this must be closely coordinated with the underfrequency load shedding schemes utilized on the host system.

After an underfrequency load shedding event, frequency relays can be utilized to automatically restore or supervise the restoration of load to a power system. Sufficient time delay should be employed to assure that the power system is stable prior to initiating load restoration.

The co-ordination of the transmission system load shedding scheme with individual generators is critical in maintaining the integrity of the system and should not intrude on the reliability of the electrical systems. Conversely, it's incumbent upon the generator owners to provide facilities that can operate at frequencies necessary to enable the load shedding schemes to operate successfully.

5.3.2 Considerations of UFLS Design

Underfrequency load shedding must be performed quickly to arrest power system frequency decline by decreasing power system load to match available generating capacity. Severe frequency decline can occur within seconds. Automatic schemes, employing frequency-sensing relays, are therefore employed to shed individual loads or blocks of load at discrete underfrequency set points or at specific frequency rates-of-decline. These set points are predetermined based on guidelines created by power pools covering a wide geographic area [88, 91].

Several issues complicate the effectiveness of underfrequency load shedding methods. One issue is that loads are not constant; they commonly vary with time of day, and day of the week. System loading may also shift, with commercial, industrial, and residential load patterns shifting during the course of the day, week, and season. Load variation makes it difficult to predict how much load will be shed at a specific time and at a specific location on the power system. Another issue that is increasing in relevance is distributed generation. Small generators, operating in parallel with utility sources, are being installed at customer load sites as a source of standby power, and a source of income where customers are selling generated power to the utility, or sharing generated power locally among cooperative groups of customers. Tripping circuits that have active parallel generation certainly diminishes the beneficial affect of load shedding, and may even be counterproductive because it eliminates sources of generation that are supporting the system inertia. Market forces may not be sufficient to assure that generation is adequately distributed throughout islands that may form during major disturbances. If the imbalance is significant, load shedding will not be effective [89, 90].

Traditional underfrequency load shedding methods are static in that they perform a specific, preset function at a specific location. The nature of modern power systems requires dynamic and adaptive underfrequency load shedding methods. Modern microprocessor based relays with integrated communication offer new possibilities to create adaptive and dynamic load shedding schemes.

5.4 Study System Frequency Characteristics

A 23 bus sample system in PSS/E is used in the study. Fig. 5-3 is the one-line diagram of the system. In this system, the total generation is 3258MW+j964MVAR and the total load is 3200MW+j1950MVAR. Four 250MVA, 100MW D-SMES [76] will be installed at the generator buses 101, 102, 206 and 211. The reason for using D-SMES rather than a concentrated SMES is to coordinate the UFGC locally.

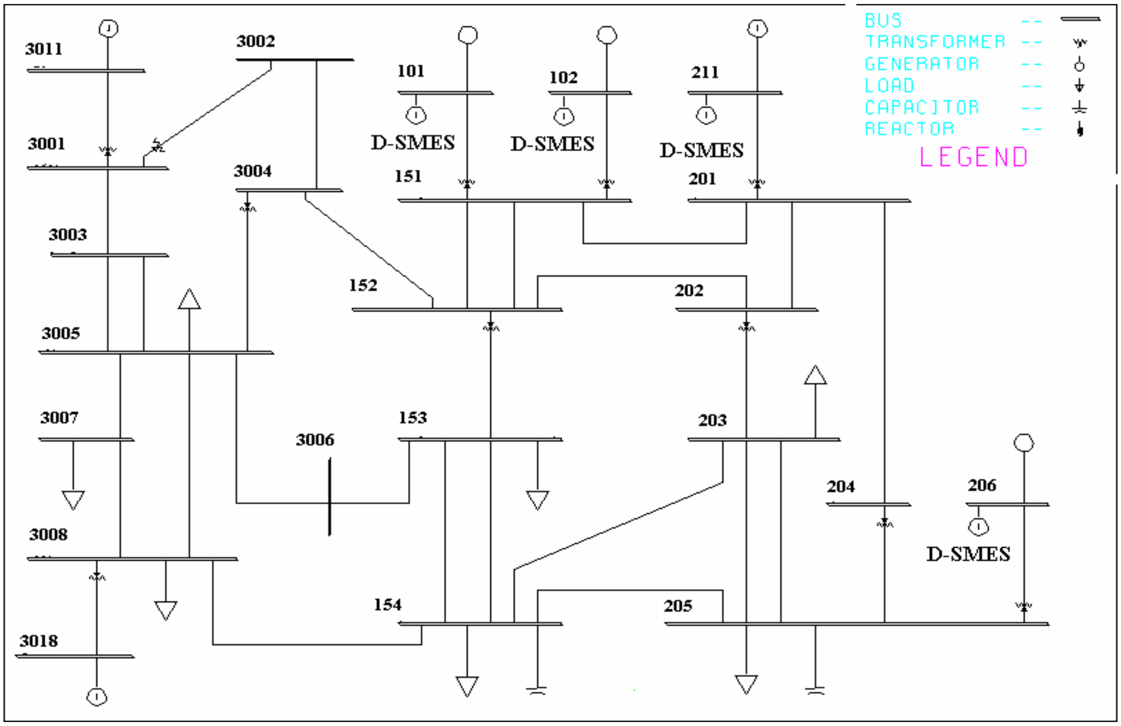


Fig. 5-3. One-line diagram of the sample research system

Information about generators and loads in the system is listed in Table 5-1 and Table 5-2 respectively. In Table 5-1, Gen.206 (generator connected to bus 206) has a high reactive power output (600MVAR) that may cause obvious change of the system voltage when it is tripped out of the system.

Table 5-1. Generators information in the system

Gen Bus No.	P_G (MW)	P_G%	Q_G (MVAR)	Q_G%
101	753	23.1	81	8.4
102	753	23.1	87	9
206	800	24.6	600	62.2
211	600	18.4	17	1.8
3011	258	7.9	104	10.8
3018	100	3.1	80	8.3

Table 5-2. Load information of the system

Load Bus No.	P_L (MW)	P_L%	Q_L (MVAR)	Q_L%
153	200	6.3	100	5.1
154	1000	31.3	800	41
203	300	9.4	150	7.7
205	1200	37.5	700	35.9
3005	100	3.1	50	2.6
3007	200	6.3	75	3.8
3008	200	6.3	75	3.8

According to the PSS/E software requirement, the constant MVA load is not realistic for voltages below 0.8 per unit. The constant load in Table 5-2 has been converted into 50% constant current load and 50% constant admittance load according to the following rules [66].

$$S_I = \frac{aS_P}{v} \tag{5-1}$$

$$S_Y = \frac{bS_P}{v^2} \tag{5-2}$$

Where S_P is original constant load. a and b are load transfer fractions. v is magnitude of bus voltage when load conversion is made. For the dynamic characteristics of the above load mix, the change of voltage and frequency may cause changing the value of the active and reactive of load.

Fig. 5-4 is the frequency at 5 different buses when generator at bus 101 (referred as Gen.101) is dropped. The buses are generator buses (bus 101 and bus 211), load buses (bus 154 and bus 3005) and tie line buses (204). We can see that the frequencies of all the buses in this system have the same dynamic characteristics, which is clearly seen from Fig. 5-5. So we select the frequency of bus 154 as the representative of the study.

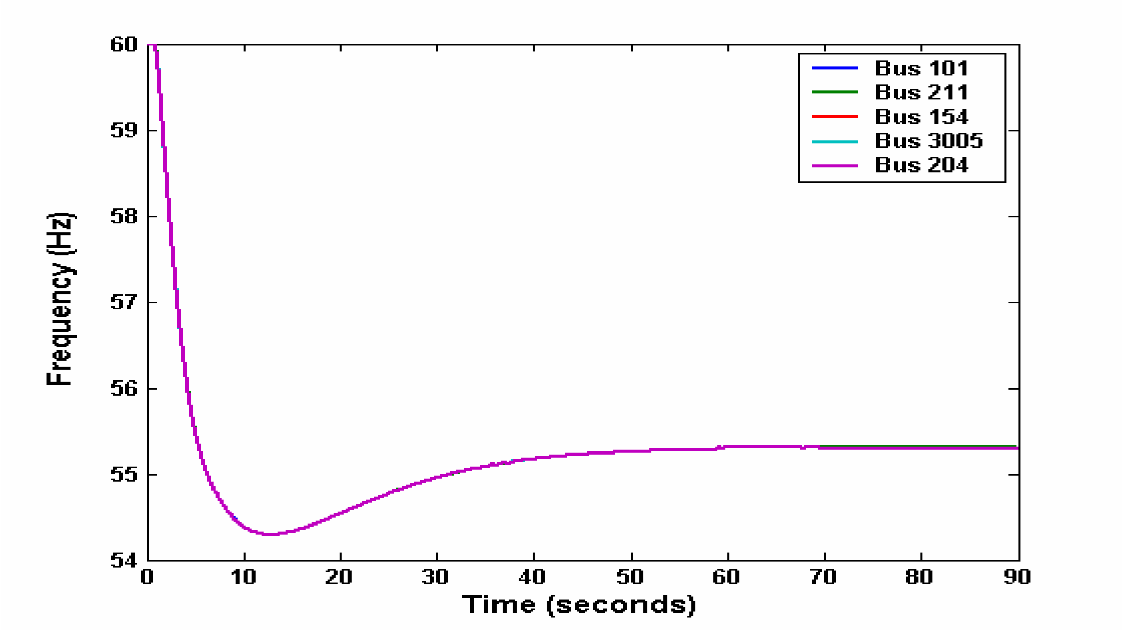


Fig. 5-4. Frequency of different buses when generator at bus 101 is disconnected

Fig. 5-5 is the frequency dynamics for all buses in the system when Gen.101 is tripped, from which we can draw the conclusion that the frequency of all the buses in the system has the same dynamic. Fig. 5-6 and Fig. 5-7 are the frequency and voltage dynamics of bus 154 when different generator is tripped from the system. In Fig. 5-6, the frequency drop caused by Gen.206 tripping is much lower than that caused by Gen.211 tripping even though the active power of Gen.206 (800MW) is much larger than that of Gen.211 (600MW). The reason lies in the fact that larger reactive power (600MVAR) has been dropped from the system when Gen.206 is tripped. That causes the voltage of the whole system dropping to a very low level (from 0.94 pu to 0.8 pu), which is shown in Fig. 5-7. The whole load of the system will become smaller because of the dynamic load characteristics mentioned above. The sudden drop of Gen.206 causes large voltage drop that the frequency rises above 60 Hz at the beginning of the dynamics.

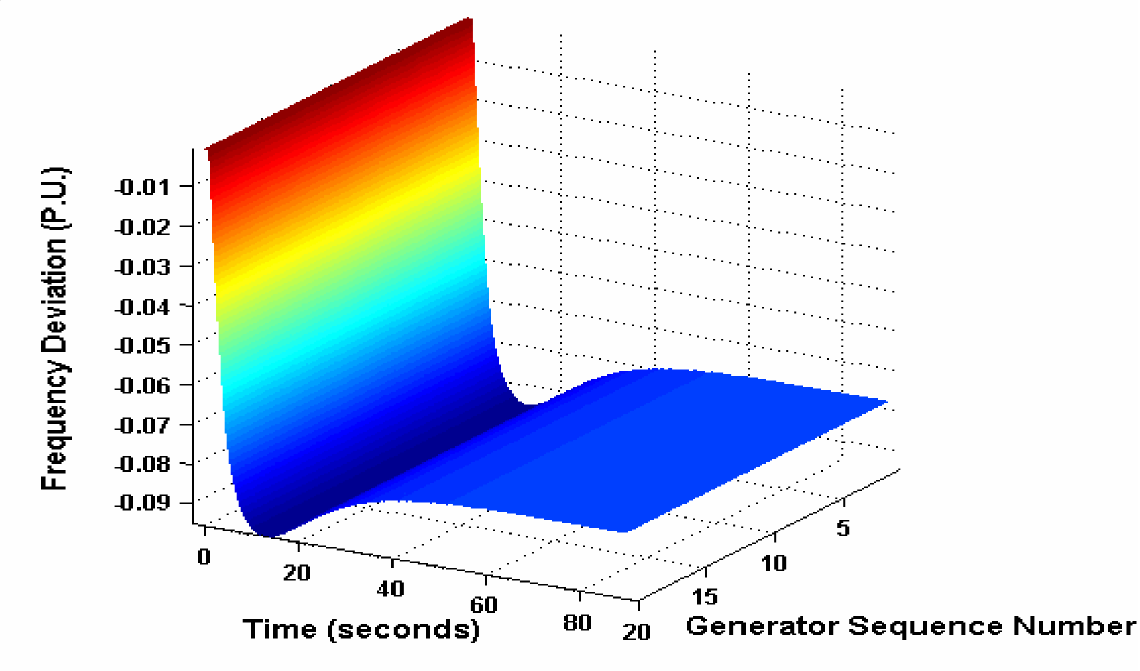


Fig. 5-5. The frequency dynamics of all the buses in the system when Gen.101 is tripped

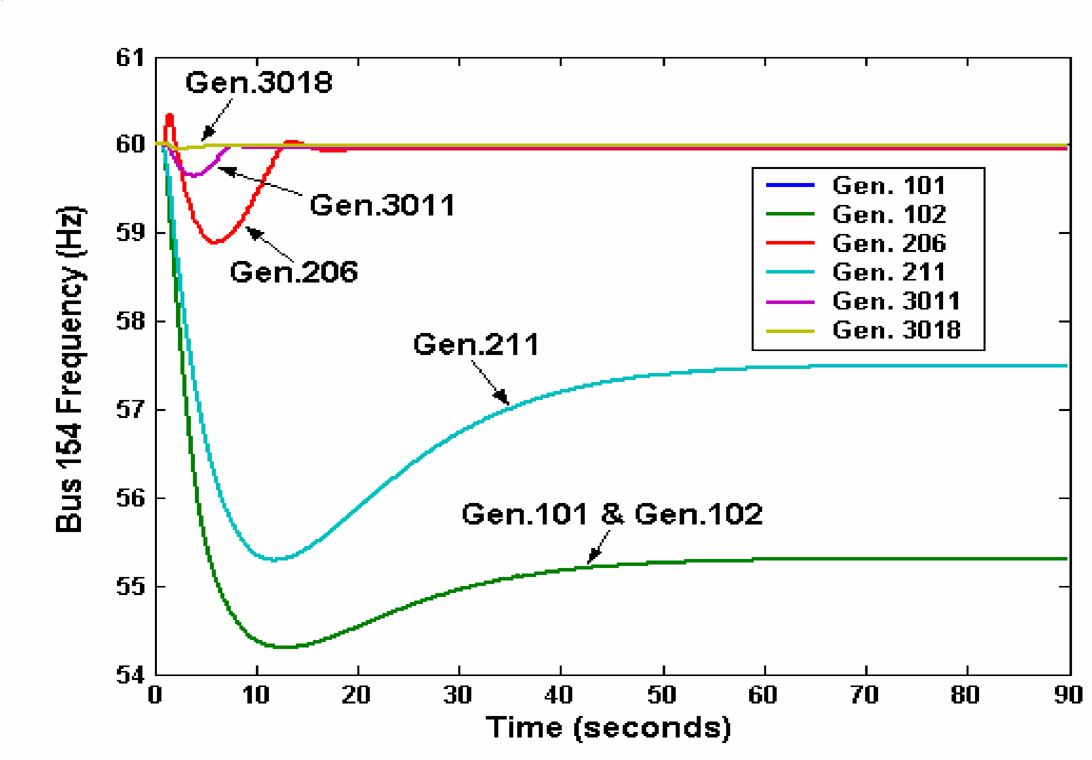


Fig. 5-6. Frequency of bus 154 when different generator is disconnected from the system

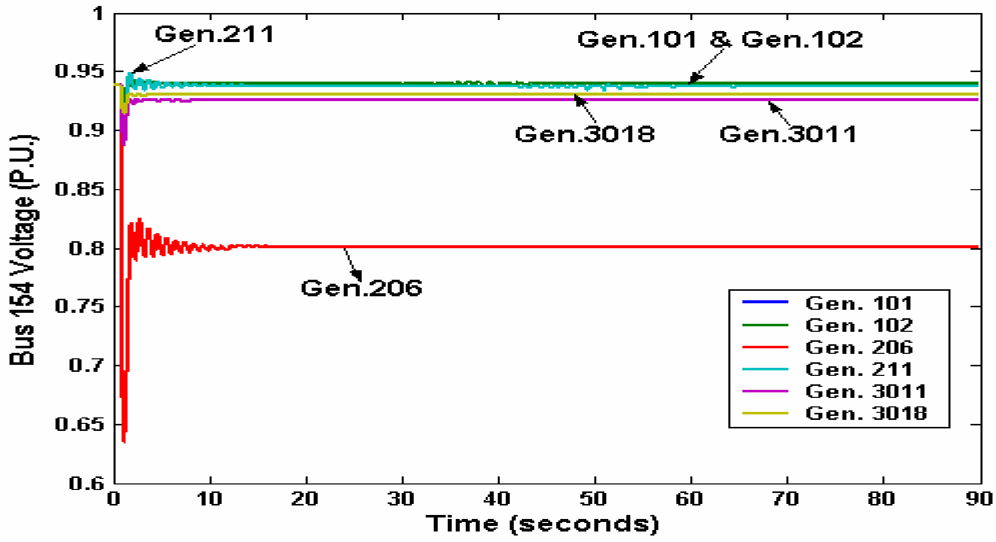


Fig. 5-7. Voltage of bus 154 when different generator is tripped from the system

During the frequency dynamics in Fig. 5-6, the frequency will recover to some level because the output of the UFGC will increase from the frequency drop. Fig. 5-8 is the dynamic governor output of Gen.101, Gen.102 and Gen.206 when Gen.211 is tripped. We can see that the governor output will rise to its highest point after a long time (about 20 seconds) because of the inertia. But the frequency will drop to its lowest point within a short period of time (within 10 seconds) in Fig.5-6. If there is UFLS in the system, the UFLS will act before the governor output its full reserve. That will drop more loads. That may cause the unsufficient usage of system spinning reserve. The total active power reserve of Gen.101, Gen.102 and Gen.206 is about 400MW.

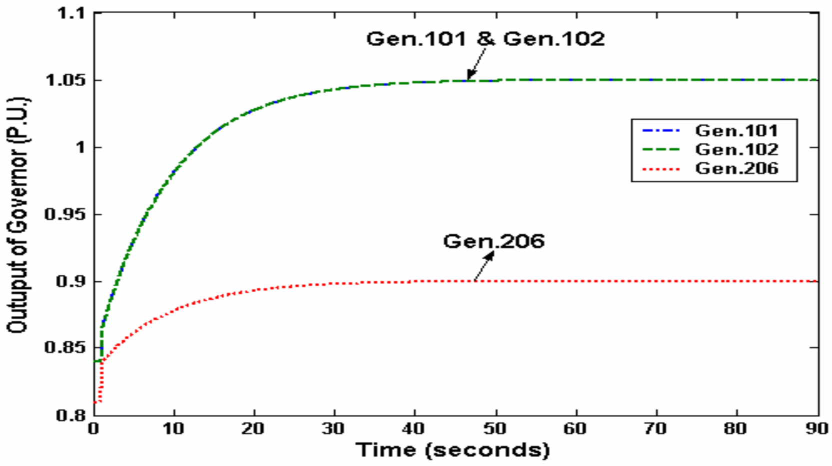
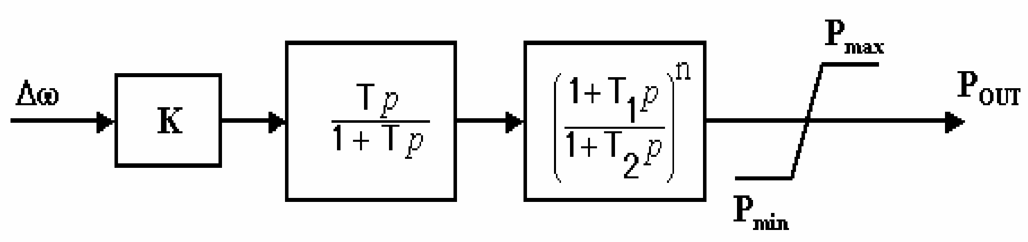


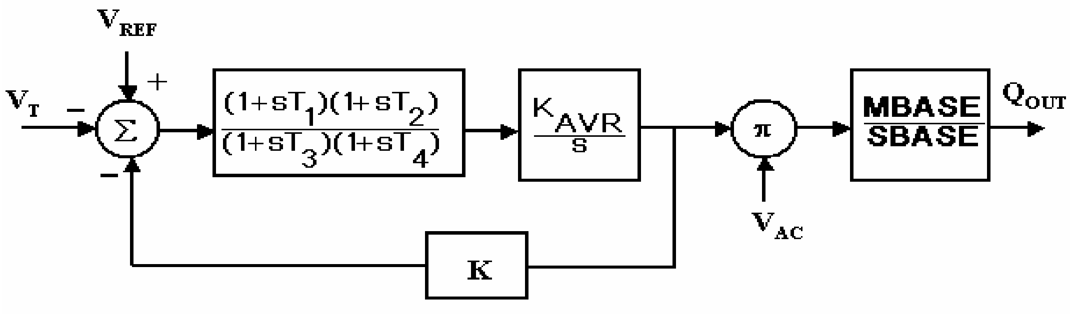
Fig. 5-8. The governor output of Gen.101, Gen.102 and Gen.206 when Gen.211 is tripped

5.5 Effects of D-SMES on System Frequency Dynamics

The control functions of the D-SMES have two parallel independent parts for active power control and reactive power control. The active power control is to control the active power output of D-SMES to stop the quick drop of system frequency. The reactive power control is to keep the terminal voltage at the reference value [66]. Fig. 5-9 is the control blocks of the two parts. In Fig. 5-9 (a), the K in the first block is the multiplying factor. The second block is the resetting block which makes P_{out} zero when t → ∞. The third block is a phase compensation block that will make P_{out} be synchronous with $\Delta\omega$. In Fig. 5-9 (b), K_{AVR}, T_1, T_2, T_3, and T_4 are the gain and time constants of the automatic voltage regulator. K is the negative feed back factor. In our case, there is no phase shift with n=0.



(a) Active power control function of FACTS/ESS



(b) Reactive power control function of FACTS/ESS

Fig. 5-9. Control function chart of FACTS/ESS controller

In this study, the 4 D-SMES are installed at the generator buses (as 101, 102, 206 and 211) as shown in the one-line-diagram in Fig. 5-1 according to the generator information in Table 5-1. In this study, we use the case of tripping Gen 211 as the sample of the study, because the generation of Gen 211 is big enough and there is no spinning reserve in Gen 211.

Fig. 5-10 is the dynamics of frequency at bus 154, Gen.101 governor output, active power output of D-SMES when Gen.211 is tripped from the system. In Fig. 5-10 the active power control of D-SMES slows down the drop of frequency and keeps it in a high level for a period of time during which the output of generator governor rises to its highest point. The frequency will continue to drop after D-SMES outputs all its active energy. But the lowest frequency is much higher than that if there is no D-SMES in the system because of the fully activation of system spinning reserve.

Fig. 5-11 is the comparison of frequency of bus 154 when Gen. 211 is tripped. The active power of D-SMES is controlled to keep a small frequency drop, 0.4 Hz for example, to keep the governor output rising.

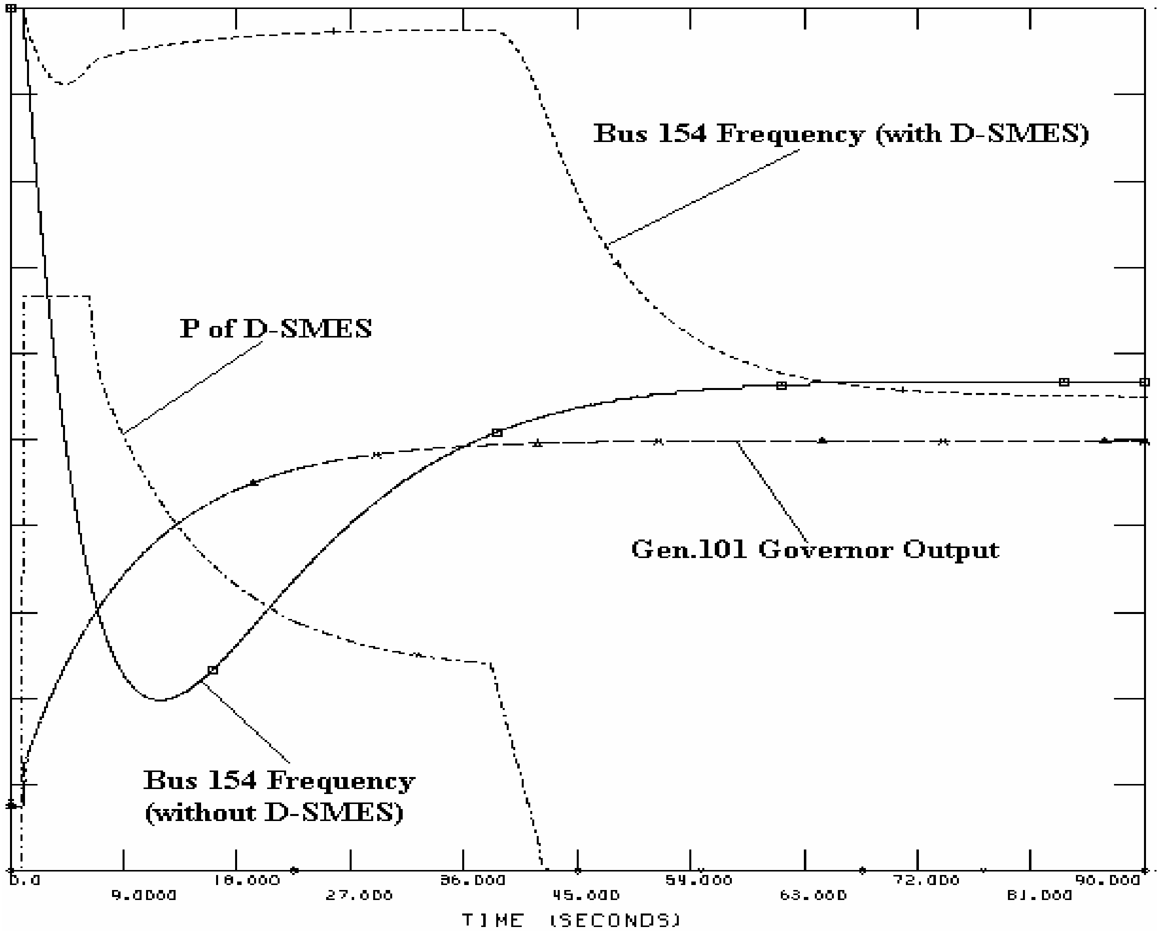


Fig. 5-10. Effects of D-SMES on the system dynamics when Gen.211 is tripped

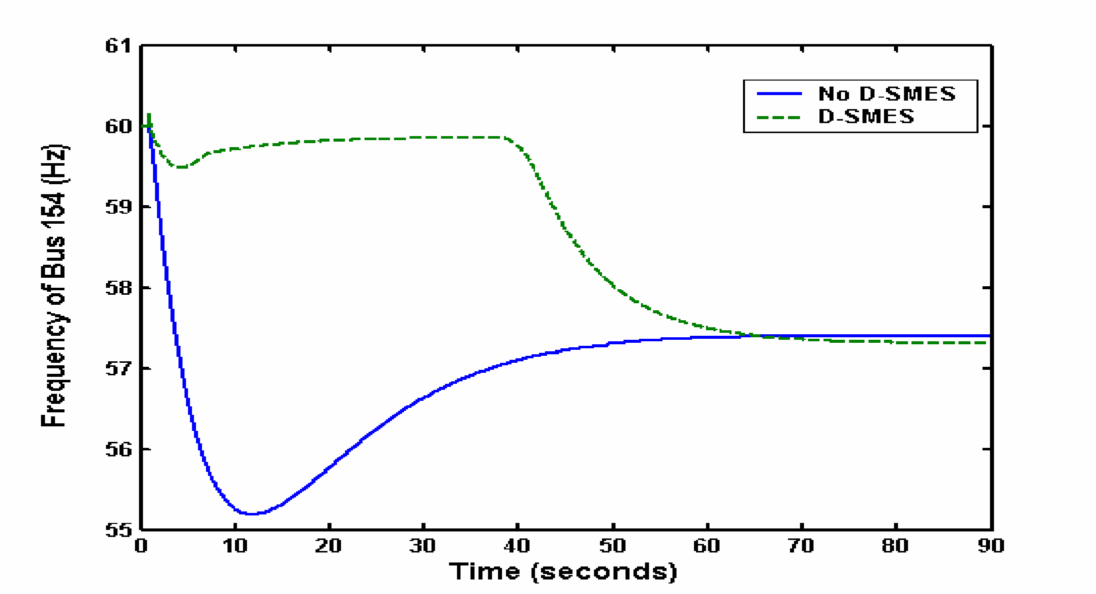


Fig. 5-11. Comparison of frequency of bus 154 when Gen.211 is tripped

Fig. 5-12 is the active power and reactive power output of D-SMES on 101 bus. The curve part (from 6.3s to 38.2 s) of active power output is controlled to keep 0.4 Hz frequency drop shown in Fig. 5-10 to keep the governor output rising. D-SMES outputs reactive power to keep the bus voltage at the reference value.

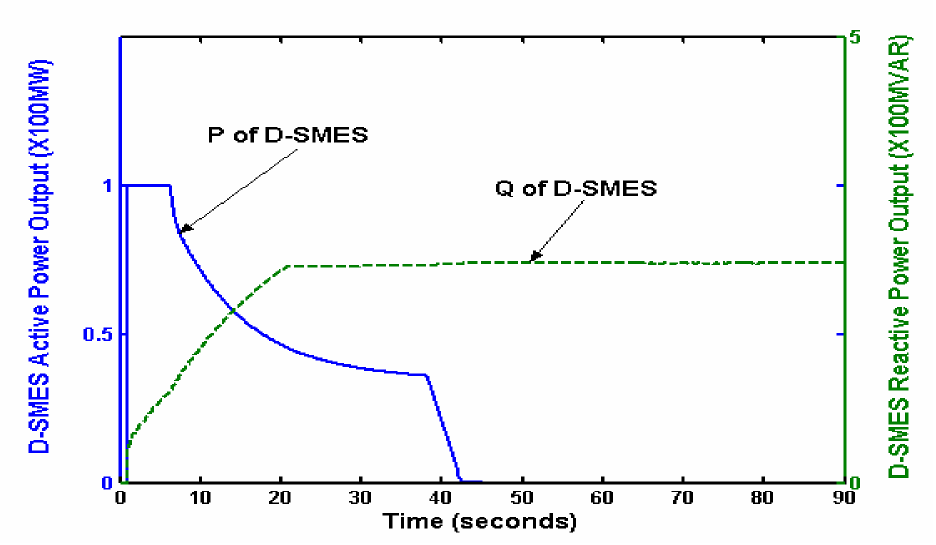


Fig. 5-12. D-SMES active and reactive power output when Gen.211 is tripped

5.6 Coordination of UFLS and UFGC by D-SMES

As we mentioned above, there is no method to coordinate UFGC and UFLS [83] before this study. Quite often this leads to an amount of disconnected load that is far more than necessary and may even lead to large frequency oscillations [82]. In this study, we use D-SMES to coordinate the UFGC and UFLS. The application of D-SMES can make the UFLS more effective to reduce the influence on power consumers by minimizing the amount of load to be shed [82]. In this study we chose a three-step UFLS scheme to study the application of D-SMES in UFLS. The UFLS scheme is shown in Table 5-3.

Table 5-3. UFLS scheme table

Step	f_i (Hz)	t_i (s)	P_{LSi} (%)
1	59.5	0.2	9
2	59.0	0.2	8
3	58.5	0.2	8

Fig. 5-13 is the UFLS protection result when Gen.211 is tripped if there is no D-SMES in the system. From the figure of load on bus 153, we can see that all the three load-shedding steps shed 25% of the total load. Even though the governor output begins to rise after the drop of Gen.211 but it stops and drops to almost the original level because the quick action of ULFS improves the system frequency to almost 60 Hz. In this situation, almost no system spinning reserve has been activated to restore the system frequency to its normal value. At the beginning of dynamics the drop of load on bus 153 is caused by the voltage dip because of the load dynamic characteristics mentioned above.

Table 5-4 shows the protection effects of the UFLS if there is no D-SMES in the system. We can see that very large amount of load that is far more than necessary has been shed. But the governor does not output its full active reserve. For example, there is about 380 MW active power reserve left for Gen.101, Gen.102 and Gen.206 when Gen.211 is tripped. That is shown clearly in Fig. 5-13.

Table 5-4. Effects of UFLS action (There is no D-SMES)

Tripped Gen.	Action Steps	f_{min} (Hz)	f_{final} (Hz)	Shed Load (%)
101	3	58.0	59.5	25
102	3	58.0	59.9	25
206	2	59.0	60.0	17
211	3	58.3	60.0	25
3011	0	59.6	59.96	0
3018	0	59.9	59.99	0

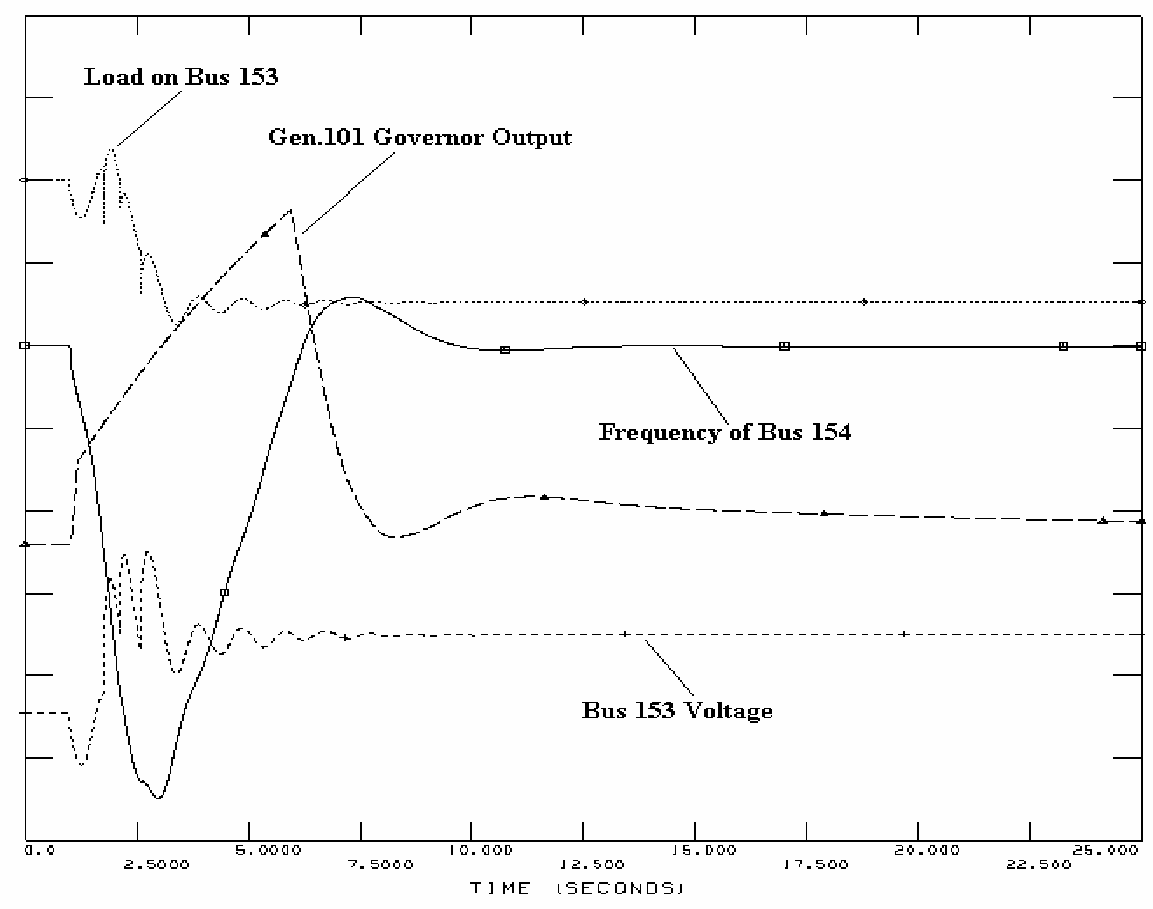


Fig. 5-13. Results of UFLS protection when Gen.211 is tripped (There is no D-SMES in the system.)

In Fig. 5-14, the load on bus 153 has been dropped 9% by the first UFLS step. The combination of D-SMES and governor prevent the system frequency dropping to the second shedding setting point of 59.0 Hz that is shown in Fig. 5-15. The activating of system spinning reserve restore the frequency to its normal value during which D-SMES runs almost out of its storage energy which is shown in Fig. 5-16 and Fig. 5-17.

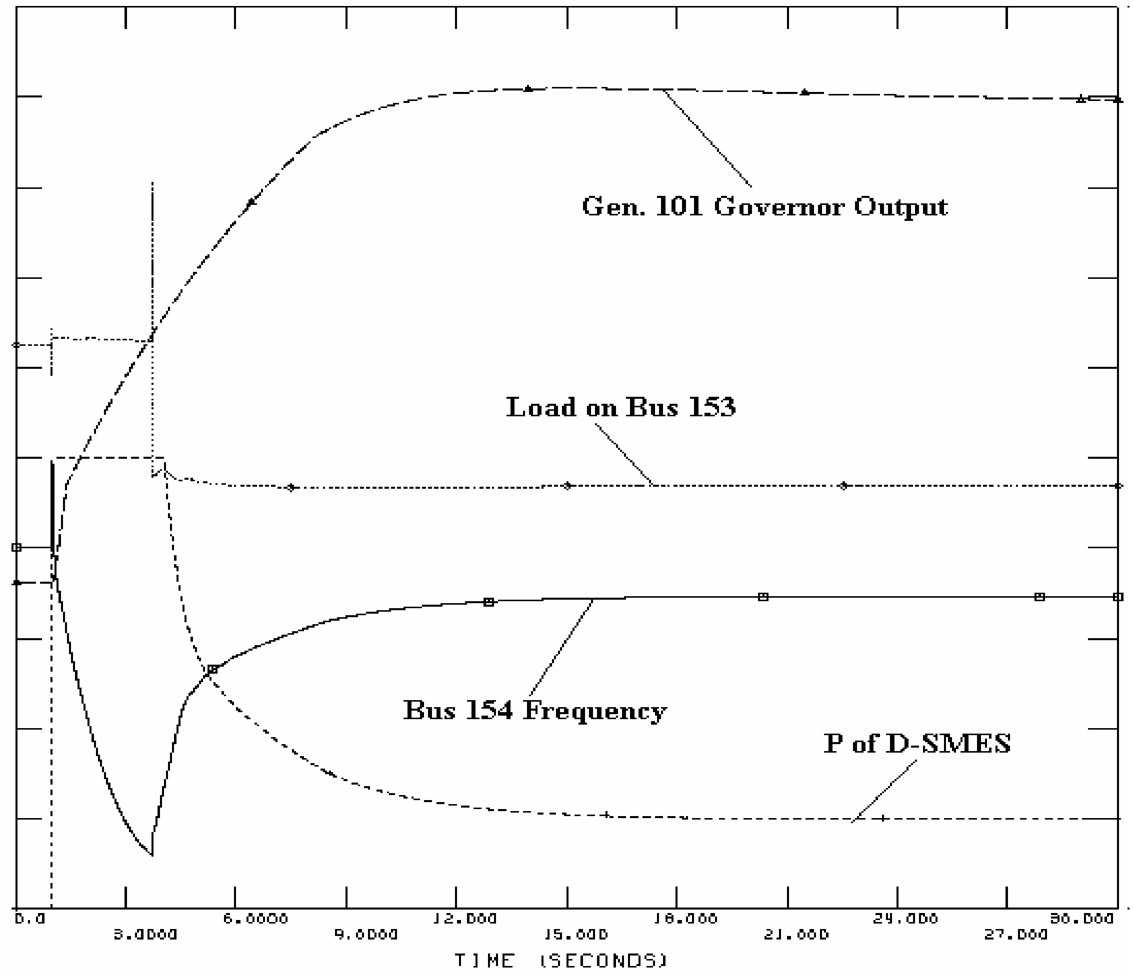


Fig. 5-14. Results of UFLS protection when Gen.211 is tripped (There are D-SMESs on the generator buses.)

Table 5-5 shows the effects of the UFLS when there are 4 D-SMES in the system. We can see that with the help of D-SMES, the generator governor can output its most spinning reserve. Less load has been shed. For example, there is about 130 MW active power reserve left for Gen.101, Gen.102 and Gen.206 when Gen.211 is tripped and the UFLS acts. About 324MW spinning reserve has been activated. That is shown clearly in Fig. 5-14.

Table 5-5 Effects of UFLS action (There is D-SMES)

Tripped Gen.	Action Steps	f_{min} (Hz)	f_{final} (Hz)	Shed Load (%)
211	1	59.46	59.93	9

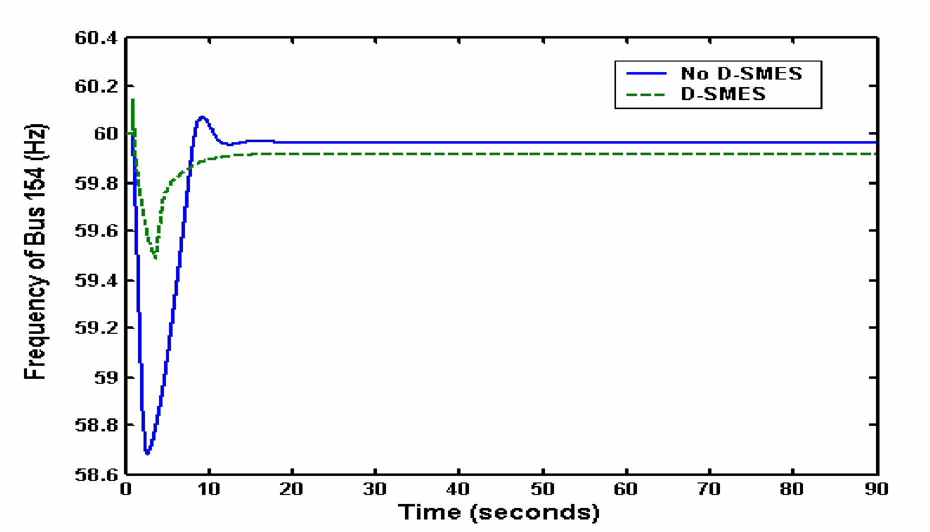


Fig. 5-15. Comparison of Bus 154 frequency for different situations under UFLS when Gen.211 is tripped

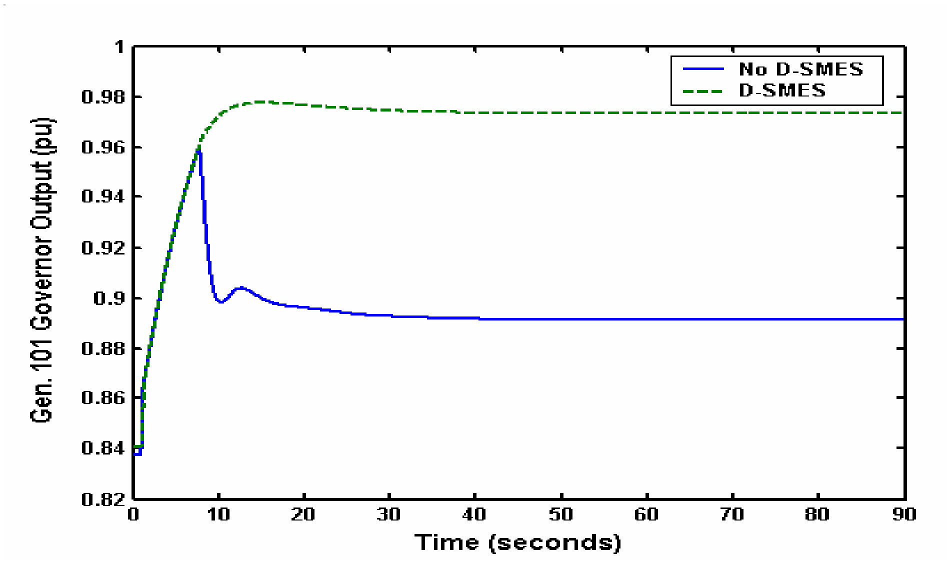


Fig. 5-16. Comparison of Gen. 101 governor output for different situations under UFLS when Gen.211 is tripped

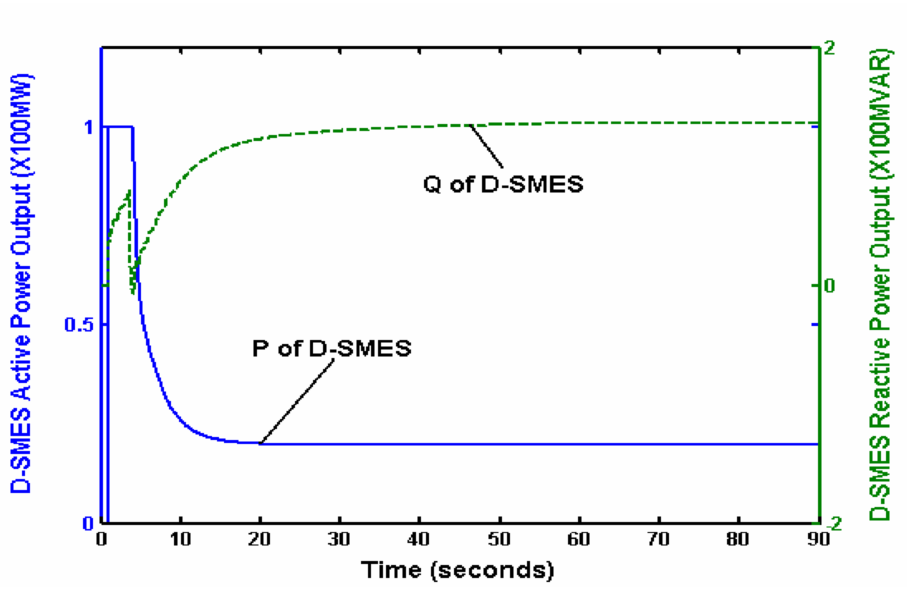


Fig. 5-17. D-SMES active and reactive power output under UFLS when Gen.211 is tripped

In Fig. 5-18, we can see that UFLS drops 25% load in three shedding steps on bus 153 if there is no D-SMES in the system. When there are 4 D-SMES in the system, the ULFS only drops 9% load in one shedding step on bus 153. The reason for the load fluctuation on bus 153 is the voltage fluctuation of bus 153 as shown in Fig. 5-13. The voltage fluctuation changes the value of the load as explained above.

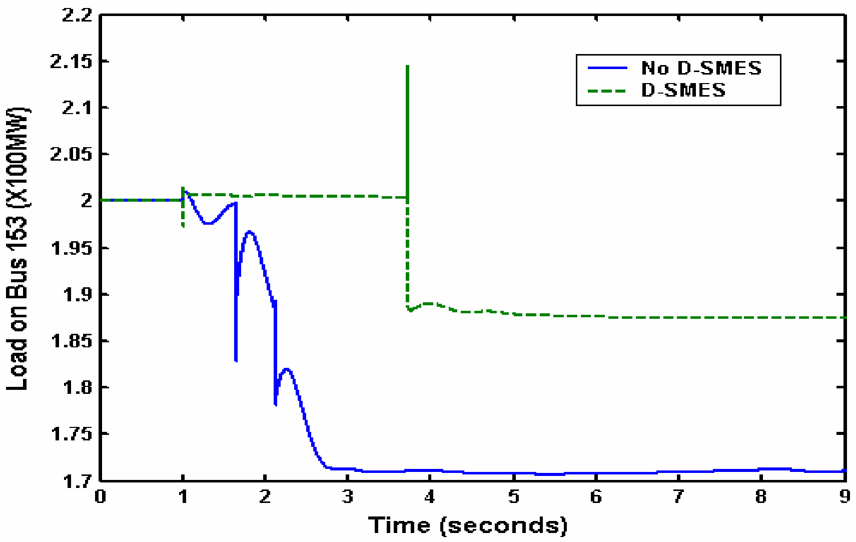


Fig. 5-18. Comparison of load on bus 153 for different situations under UFLS when Gen.211 is tripped

Fig. 5-19 shows the results of UFLS protection when Gen.102 is tripped. Fig. 5-19 is the typical SMES application scenario. The coordination of SMES and activating system spinning reserve prevents the system frequency dropping to the second UFLS step setting point (59.0 Hz) before SMES runs out of its storage energy. The drain of SMES energy causes a new quick drop of frequency. Fortunately, the output of governor reaches its maximum point at this time and the new drop of frequency just causes one step action of UFLS (the second step). After that the system frequency restore to its normal value. In this situation, the actions of two UFLS steps have a long time interval.

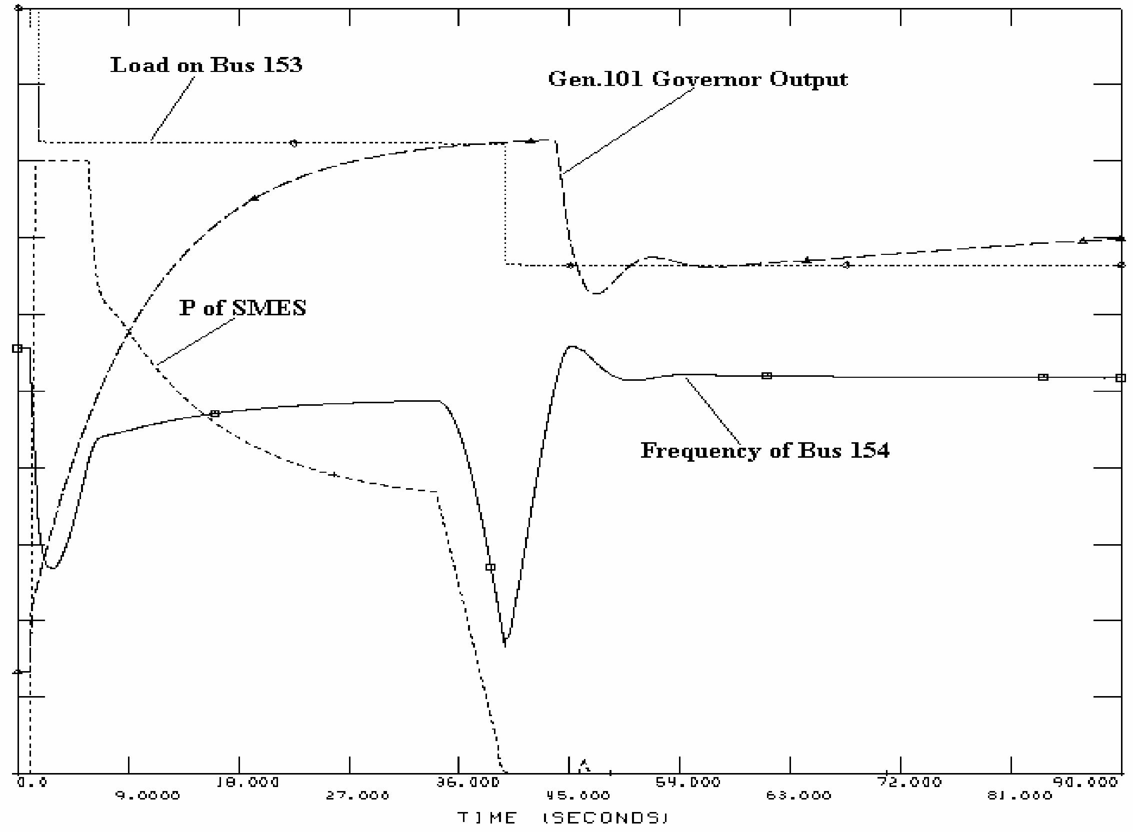


Fig. 5-19. The result of UFLS when Gen.101 is tripped (There is SMES.)

5.7 FNET Application In This Study

5.7.1 FNET Introduction

The GPS/Internet based frequency network (FNET) in Fig. 5-20 consists of two major components: (1) frequency disturbance recorder, FDR, and (2) the Internet based information management system (IMS). Frequency measurements are taken at 110V single-phase power outlets with the high accuracy frequency disturbance recorder (FDR). The crucial innovation in FNET is to make accurate frequency measurement from the 110 V outlets. As a consequence, many obstacles (cost, time delays) associated with high voltage substation installations are avoided. FNET costs only a fraction of what would be typically required to get global dynamic frequency information and, thus, allow measurements to be made at a large number of locations. For example, at TVA, the installed cost of one PMU in 2004 is over $80,000. Installed cost of one FDR with GPS and network capability is only 1-3% of that number.

FNET offers breadth of area coverage by giving up certain parameters such as tie line flows offered in a high voltage substation phasor measurement unit (PMU).

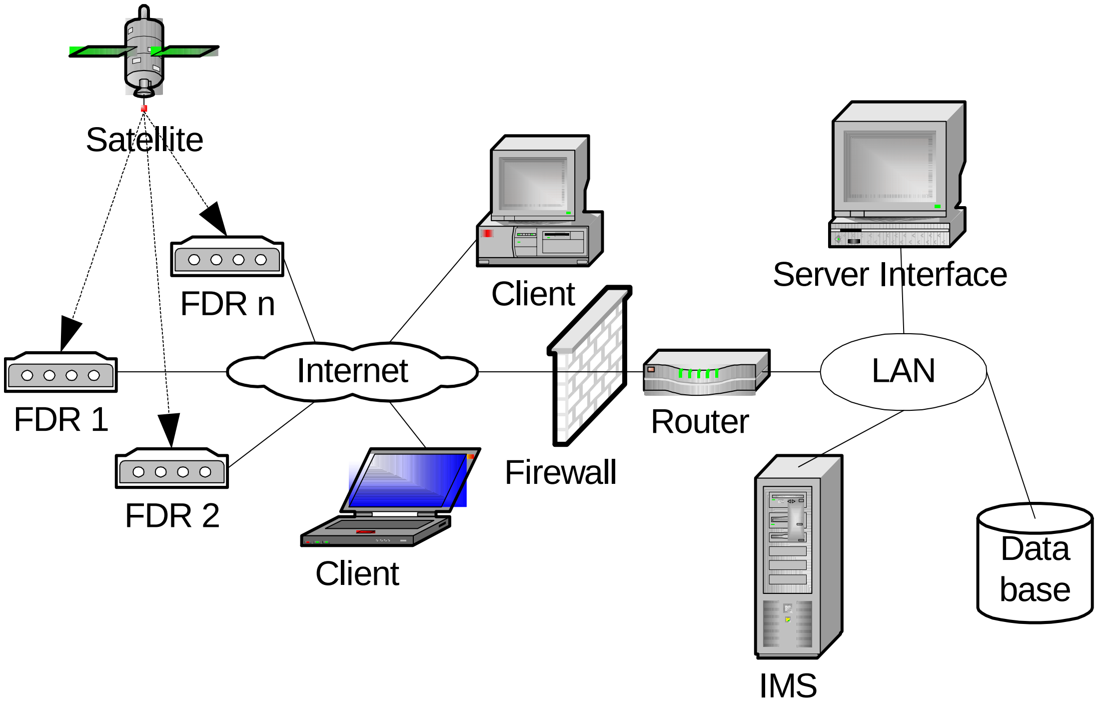


Fig. 5-20. The GPS/Internet based FNET configuration

Frequency disturbance recorder (FDR) was developed at Virginia Tech. As shown in Fig. 5-21, the FDR consists of a voltage transducer, a low pass filter, an A/D converter, a GPS receiver, a processor, and the network communication module. The voltage transducer takes analog voltage signals off the 110V wall outlets, filters and converts them into digital data. The Low-Pass filter eliminates high frequency noise and acts as an anti-aliasing filter. The filter removes high frequency noise from the voltage waveform, which may experience at the 110V-level. In the microprocessor, information, including the rate of frequency change, voltage and angle, are computed using Phasor Techniques developed at Virginia Tech [85, 86]. The frequency and angle are time tagged, and transferred to the main server via the Internet. The first FDR unit like the one shown in Fig. 5-22 was deployed in November 2003. GPS synchronization permits precise comparison of data taken from anywhere in the system. The FDR has a sampling rate of 1.44 kHz (24 points/cycle), dynamic frequency accuracy within ±0.0005 Hz, and time synchronization within 1ms. Obviously, frequency measurement does not require such a level of time precision. However, it is intended for synchronized relative voltage angle measurements. The required accuracy of synchronization can be determined so at 60Hz, a sampling error of 1 ms corresponds to an angular error of 0.0216 degrees (0.018 for 50 Hz system). Right now, FDR output is at 10 data sets (time stamp, voltage, angle, frequency) per second.

The most valuable information is what will be collected during a system disturbance. The fast changing nature during system dynamics requires shorter measurement window to reflect true system status, the algorithms used in the FDRs ensures measurement accuracy with less data.

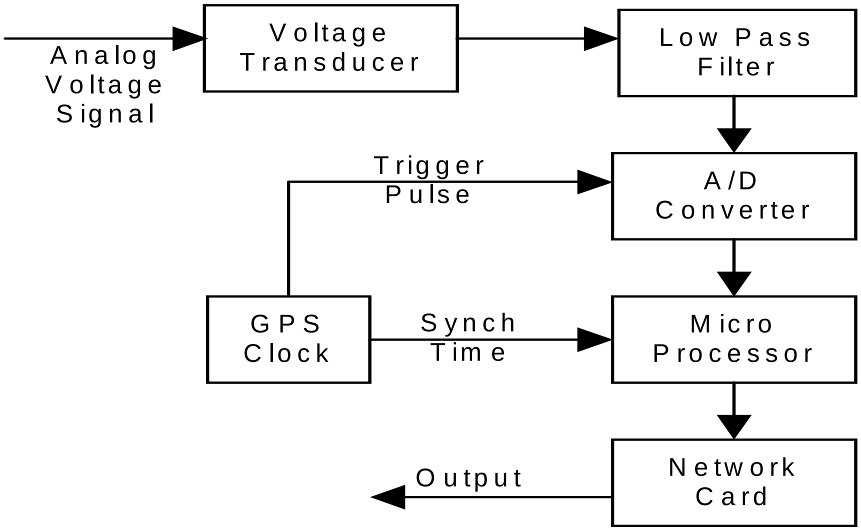


Fig. 5-21. Frequency disturbance recorder (FDR) structure

Fig. 5-22. Frequency disturbance recorder (FDR) outline

5.7.2 FNET Application

Continuous synchronized quasi real-time wide area frequency information can be very valuable in many different ways. In summary, information from FNET can help to: (1) gather first-hand wide-area information for understanding the fundamental characteristics and mathematics of failures of complex power systems; (2) provide system operators all over the country with close real-time system status; (3) analyze the underlying causes of cascading events and system failures (blackouts), perform post disturbance scenario reconstruction, and track the sequence of events leading to an emergency; (4) provide information for validation of system models and parameters used in the mathematical analysis and simulations; (5) supply theoretical basis and evaluating platform for various power system control functions such as load shedding, system restoration, and automatic generation control; (6) provide wide-are picture of system performance for designing system-wide countermeasure schemes; (7) provide field data to validate wave propagation theory and study desirable wave-reflection conditions to damp system oscillations; (8) supply references for AGC and FACTS control actions.

The FNET system provides power system researchers, operators, customers, and policy makers a relatively easy-to-access, cost-effective, cross-platform frequency information monitoring network on the Internet. Such information access capability was never possible before.

FNET uses GPS-synchronized phasor measurement technologies and communication infrastructure of today. The experience from FNET development will help further evolving the power system information network.

5.7.3 FNET Application in This Study

FENT can be applied as the data and information transmission media in the coordination of UFLS and UFGC by using D-SMES. A FDR is installed near each D-SMES transferring local frequency data to control center. The control center will coordinate all the distributed SMES based on the frequency information within wide area system. The draft application of FNET in this study is shown in Fig. 5-23.

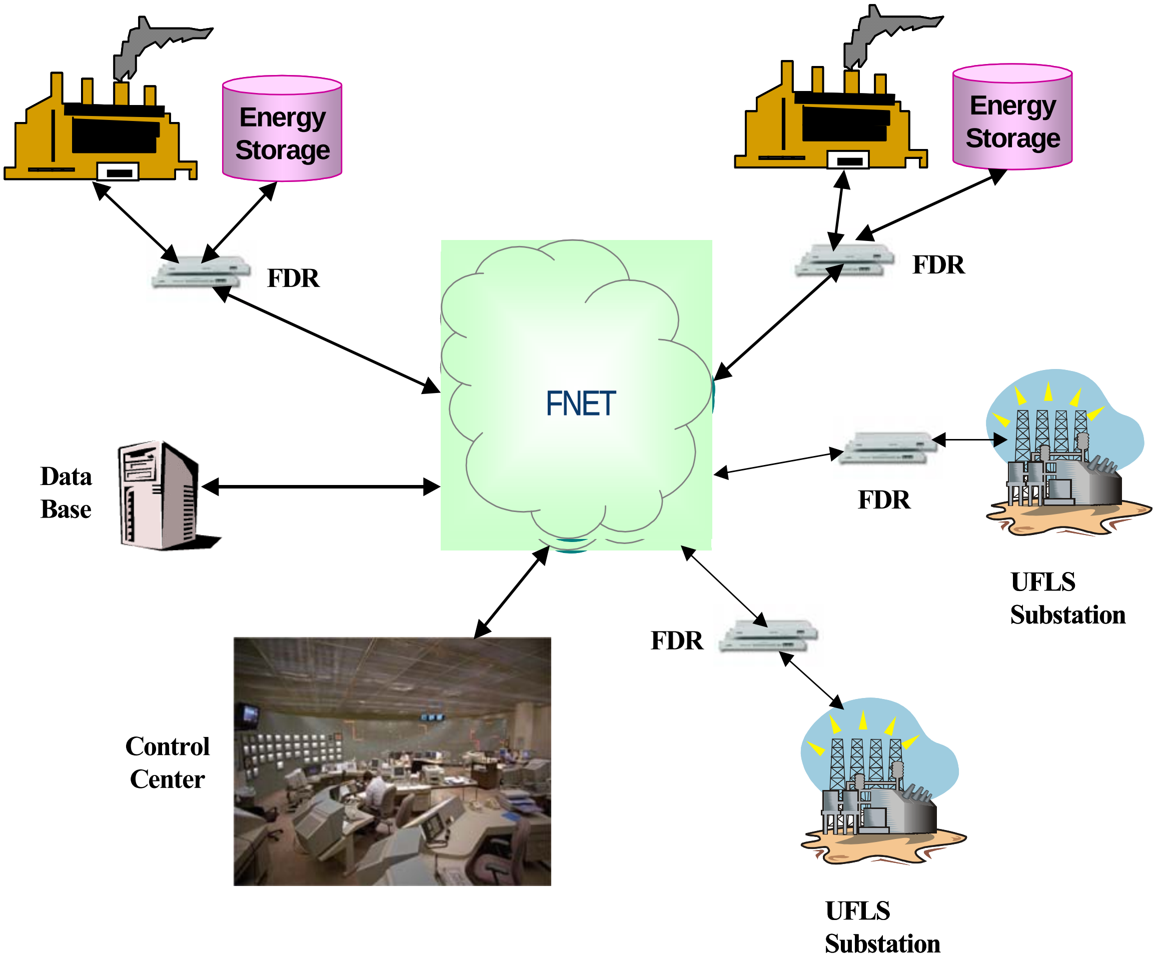


Fig. 5-23. FNET application in coordination of UFLS & UFGC by using D-SMES

5.8 Summary

UFGC and UFLS are two general control schemes to restore power system frequency to the normal value when generation-load unbalance causes drop of system frequency. UFGC is used to activate the system spinning reserve and UFLS is used to shed an amount of load to stop the dropping of the system frequency. Even though UFLS serves as the last-resort to prevent the system from collapse when a sudden loss of generation causes a deviation of frequency, UFLS acts before the full action of UFGC because of the quick drop of frequency.

The application of D-SMES can coordinate the UFGC and UFLS to achieve the goal of full activating the spinning reserve and minimizing shedding load. The reason for using the D-SMES rather than the one concentrated SMES is to coordinate with UFGC locally.

In this study, the author studied the coordination of UFLS and UFGC by application of D-SMES. The active and reactive power controls of D-SMES are independent. The active power is controlled to stop the dropping of system frequency and the reactive power is control to stabilize the local voltage.

The research results show that D-SMES can slow the quick drop of system frequency and hold it for the full activation of system spinning reserve. That can help the governors output their maximum reserve before UFLS drops more load which results in minimized load shedding.

The author uses a 23 buses sample system in this study. For the bulk power system, the coordination of UFLS and UFGC by application of D-SMES will be more complicated which will be the future research task.

The potential application of FENT in the coordination of UFLS and UFGC is discussed in this dissertation as well.

Chapter 6. Wide Area Voltage Control by FACTS/ESS

6.1 Background

6.1.1 Voltage Problems in the Knoxville Region of TVA

The Knoxville (Tennessee) area consists of the loads served from the Knoxville Primary, North Knoxville, Nixon Road, Lonsdale and West Hill 161 kV substations. Fig. 6-1 is the layout of the system in this research region. The map includes the TVA 500 kV as well as the 161 kV lines.

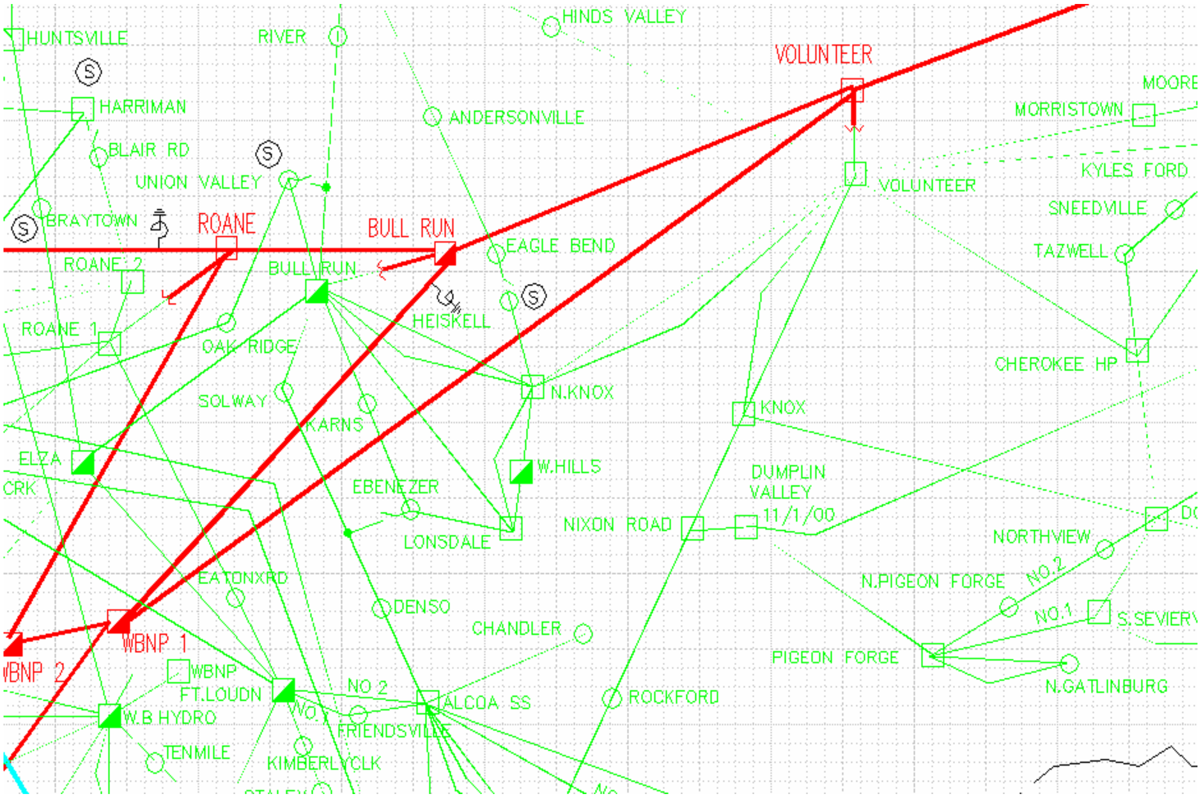


Fig. 6-1. The network layout of the system in the Knoxville area

The Bulk Transmission Planning staff at TVA has studied this area in the past. The analysis by TVA showed that there is significant potential for voltage problems at both summer and winter peak load conditions any time after the summer of 2001. The problems will consist of both steady-state low voltage and voltage instability in Knoxville and the surrounding areas. The most severe problems occur following outage of the existing Volunteer 500-161 kV transformer with prior outage of the Bull Run generation. Without any system improvements, steady state 161 kV voltages below 95% can occur during this outage event whenever load is above 92% of 2003 summer peak levels. Similar contingency voltage may also occur at 2003 winter peak loads.

The greater Knoxville area can also experience slow voltage recovery, voltage collapse and loss of load following a fault on the Volunteer 500-161 kV transformer during a prior outage of the Bull Run generation. If the critical contingency occurs at peak 2003 summer or winter load levels the area's 161 kV transmission voltages drop to the 92-94% range for several seconds and recovers to an unacceptable voltage. The Knoxville area 69 kV and 13 kV distribution voltages drop even further to the 70-90% range. Transmission, sub-transmission and distribution system voltages in these ranges will result in either loss of load or damage to customer equipments or both. Voltages will not return to acceptable levels until large blocks of load are shed in response to the sustained low voltage.

The 2003 summer system was tested for the simultaneous outage of both the Bull Run generation and the Volunteer 500-161 kV transformer. At 2003 summer peak load conditions, this outage is very severe which is treated as the most critical contingency. It means that the 161 kV voltages would be less than 94% of nominal.

In addition to the steady-state low voltage problems identified above, the Knoxville area could also experience voltage collapse following a fault on the Volunteer 500-161 kV transformer. Comparing with the reported voltage collapse incidents, the Knoxville area system of TVA has most of the following characteristics that may bring system voltage collapse happen.

- The Knoxville area system has been heavily loaded at the 2003 summer peak load.
- A multiple contingency (outage of Volunteer transformer and Bull Run generation, plus the three phase short-circuit fault at an important bus) is very severe.
- The outage of Bull Run generation and Volunteer transformer makes a re-distribution of power flow. It will sharply increase loading on some lines, greatly increasing their series reactive power losses. When operators are unable to reduce the flow of these lines, tripping of these lines will happen.

- There will be an abrupt voltage reduction at substations supplied by these lines.
- As a logical result, rotating unit reactive power output will increase in response to the lower voltage.

6.1.2 System Used in This Study

The Tennessee Valley Authority prepared the base case for power flow and dynamic simulation of voltage stability. According to the load flow data and dynamic data of the studied system, it is shown that this is a rather large and complicated system. It contains not only the TVA system data, but the associated system data as well. In Table 6-1, we give a statistics of the different types of data in the original load flow data file to show the scale of the system in this study. The total generation in the base case file is 544110 MW + j 128840 MVAR, the total load is 532709 MW + j195256 MVAR. This study is conducted by PSAPAC software.

Table 6-1. The statistics of the data in the raw load flow base case file

Data Type	Data Number
Bus Data	10808
Load Data	12134
Generator Data	2313
Branch Data	21496
Transformer Adjustment Data	1480
Area Interchange Data	74
Switched Shunt Data	880
Zone Data	182

6.1.3 Voltage Performance Criteria

Voltage stability is the ability of the power system to return to the nominal (pre-fault) voltages of all buses following a disturbance in the system. In addition, the system shall also be able to maintain the nominal voltage at buses in the steady state. In this study, we follow the following voltage recovery criteria based on WECC criteria, which is shown in Fig. 6-2 [93-95].

- Post transient voltage deviation 10% or less for N-2 contingencies
- Less than 20% at load buses for more than 20 cycles.
- Not to exceed 30% at any bus.

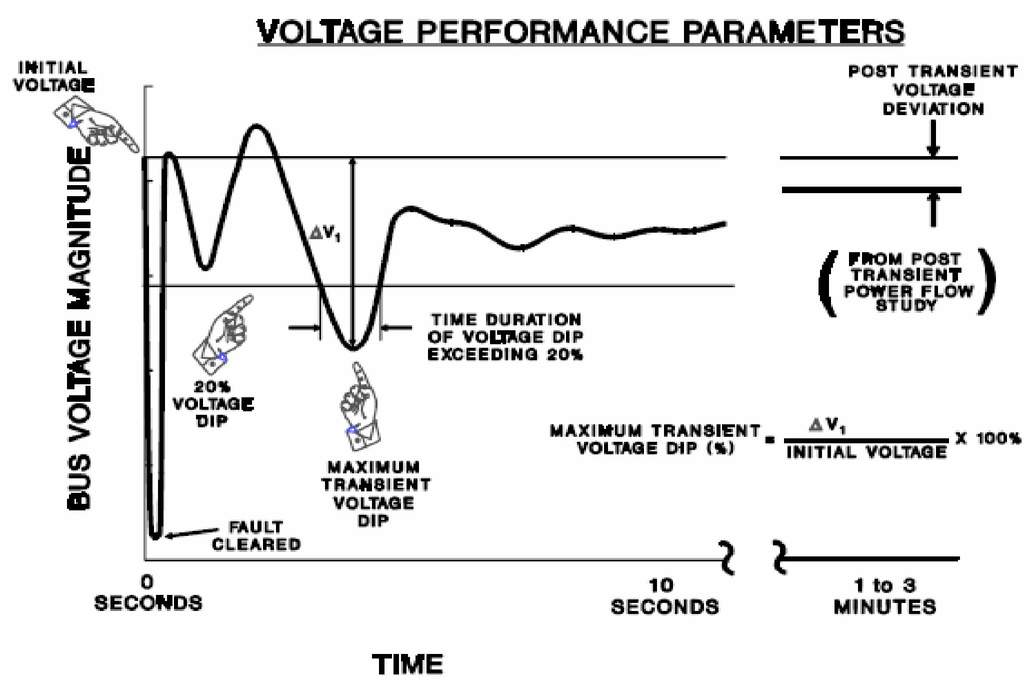


Fig. 6-2. WECC voltage recovery criteria

6.2 Steady State Analysis of Study Area System

According to the general background knowledge of Knoxville area system of TVA, we define the following 3 system operation modes and will analyze the steady state of the research region under the defined 3 system operation modes. Table 6-2 shows the active power and reactive power transfer through Volunteer 500-161 kV transformer in the above 3 different system operation modes.

- Mode 1 (no contingency): Bull Run generation plant and Volunteer 500-161 kV transformer are in service.
- Mode 2 (contingency 1): Bull Run generation plant is out of service and the Volunteer 500-161 kV transformer is in service.
- Mode 3 (contingency 2): Bull Run generation plant and Volunteer 500-161 kV transformer are out of service.

Table 6-2. P & Q transfer by the Volunteer 500-161 kV transformer in 3 operation modes

Mode	Active Power (MW)	Reactive Power (MVAR)
Mode 1	610	540
Mode 2	739	526
Mode 3	0	0

The base case has the Knoxville Utility Board (KUB) 69 kV lines and the 69-13.2 kV transformer details in the Knoxville area. According to the above system knowledge and monitoring buses, a detailed one-line diagram of the studied region system containing the 3 main voltage levels was proposed in Fig. 6-3. This is only a part of the studied region of the whole system where we focus our study. We can see that Fig. 6-3 shows Bull Run generation plant, Volunteer 500-161 kV transformer and the relationship of all the monitoring buses in Table 6-3. Table 6-3 is the monitoring bus voltage amplitude at the different 3 operation modes. Fig. 6-4 and Fig. 6-5 show the load flow in the studied region under operation mode 1 and 3.

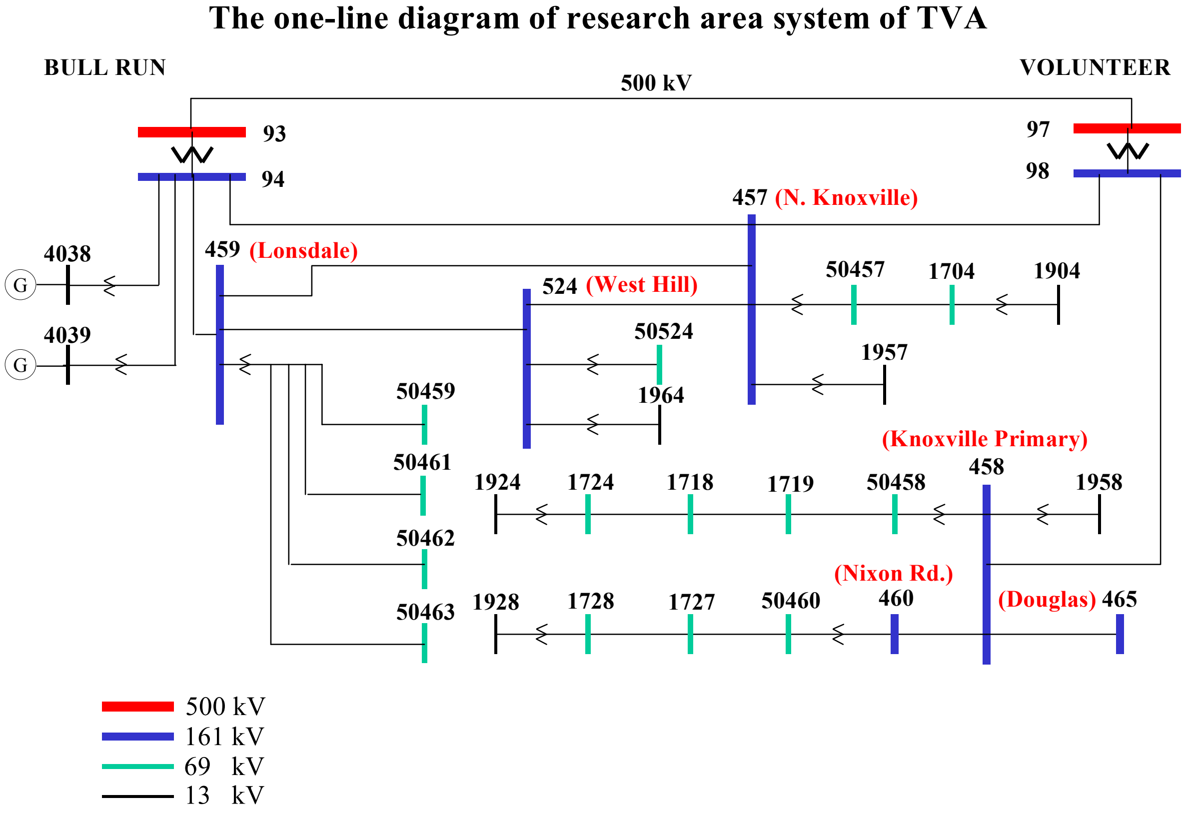


Fig. 6-3. The one-line diagram showing part of the studied region system of TVA

Table 6-3. The monitoring bus voltage magnitude at the 3 operation modes

Voltage Level	Bus Number	Bus Name	Area Name	Voltage Magnitude (P.U.) Mode 1	Mode 2	Mode 3
161 kV	98	‘5VOLUNTE’	Volunteer	1.045	1.043	0.940
	457	‘5N KNOX ‘	North Knoxville	1.017	1.012	0.945
	458	‘5KNOX ‘	Knox Primary	1.022	1.018	0.927
	459	‘5LONSDAL’	Lonsdale	1.002	0.996	0.936
	460	‘5NIXON R’	Nixon Road	0.997	0.995	0.936
	524	‘5WEST HL’	West Hill	1.005	1.000	0.935
69 kV	50457	‘N.KNOXVL’	North Knoxville	0.998	0.992	0.915
	50458	‘KNOXBR1 ’	Knox Primary	1.013	1.010	0.916
	50459	‘LONSDAL1’	Lonsdale	1.004	0.997	0.923
	1704	‘KUB04 ’	KUB04	0.985	0.980	0.895
	1724	‘KUB24 ’	KUB24	0.911	0.908	0.810
	1728	‘KUB28 ’	KUB28	0.937	0.934	0.859
13 kV	1957	‘N.KNOX ’	North Knoxville	1.014	1.008	0.934
	1958	‘KNOXBR ’	Knox Primary	1.013	1.010	0.909
	50461	‘LONSDAL2’	Lonsdale	1.011	1.004	0.937
	1904	‘KUB04 ’	KUB04	1.015	1.009	0.912
	1924	‘KUB24 ’	KUB24	1.012	1.009	0.886
	1928	‘KUB28 ’	KUB28	1.011	1.007	0.873

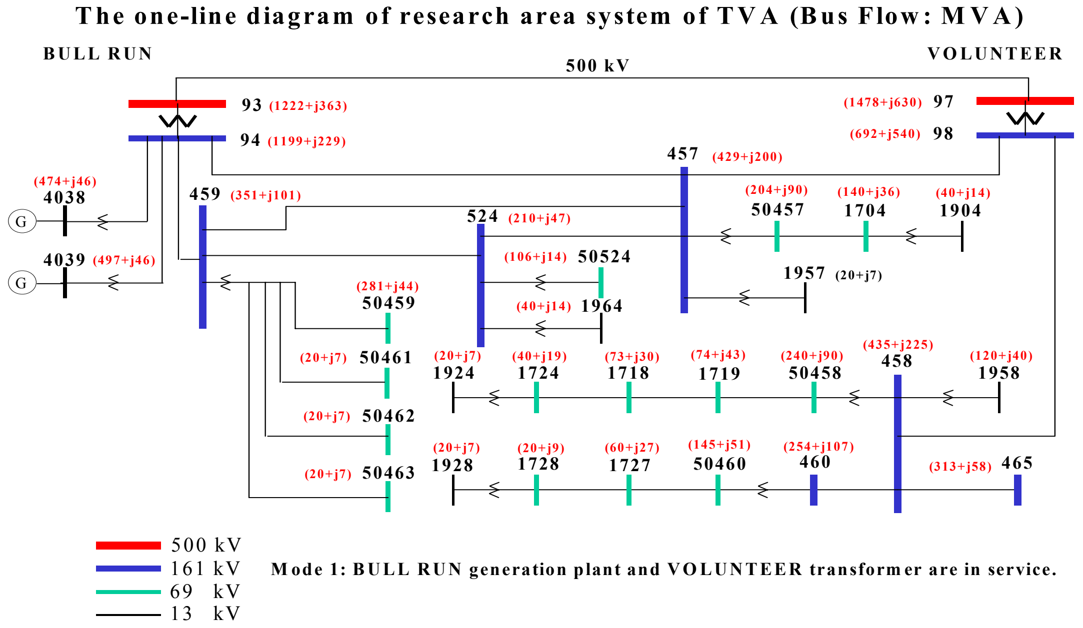


Fig. 6-4. The bus flow of the research area under system operation mode 1

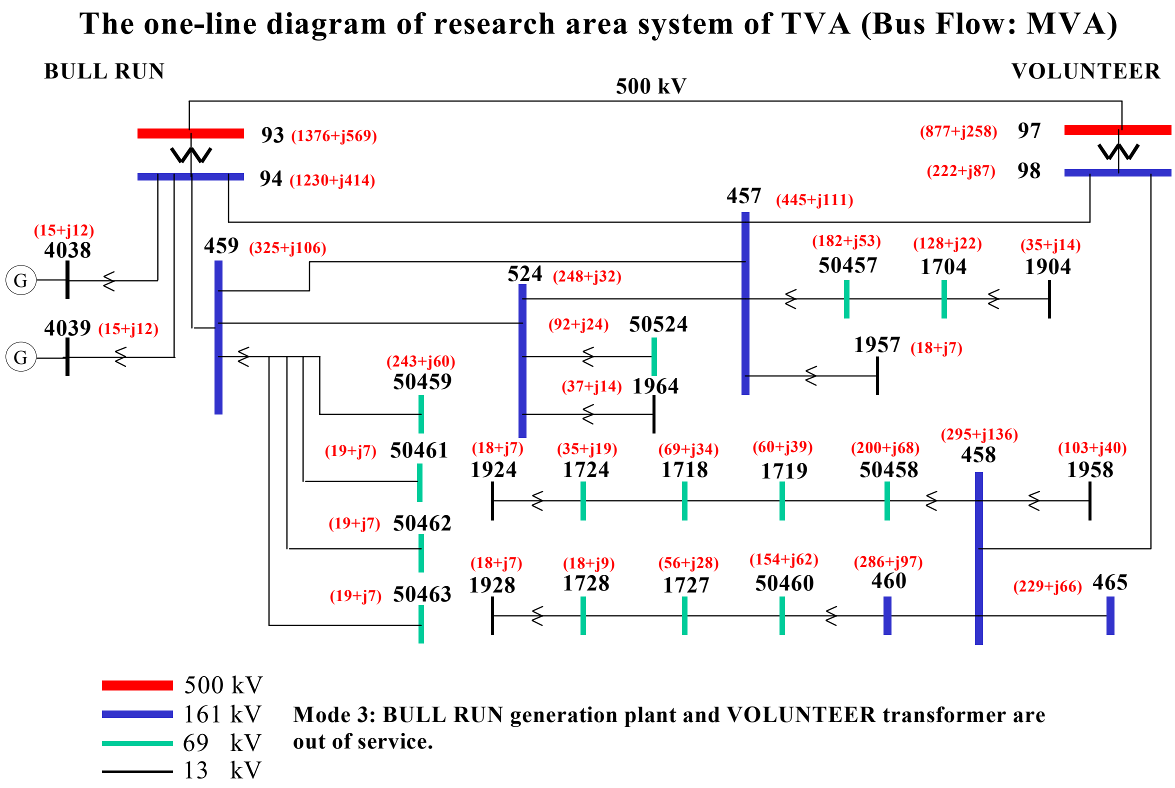


Fig. 6-5. The bus flow of the research area under operation mode 3

6.3 Concentrated Solution Evaluation By Dynamic Analysis

In this study, we first evaluate the concentrated compensation solution by dynamic analysis. The concentrated solution method means a single compensator is installed at a certain bus in this system to make the reactive power compensation supporting the voltage in the nearby system.

6.3.1 Concentrated Solution Options

It is more difficult to control the balance between the supply and demand of reactive power than the control of active power. The general active power control is to make sure the generation supplying the customer demands including the loss in the network. Voltage stability is dealing more load behavior rather than the machine rotor behavior, which is the focus of traditional machine stability study is dealing with.

In modern power networks, generators are usually large and far away from major load centers. Many constrains limit the possibility to build power plants near the load center. Large amount of load will be transferred through long distance lines from generation center to load center. It is almost impossible to control the load center voltage by controlling the generator output in the far away generation center. The practical way is to use the nearby reactive power sources. In fact, there are five distinct components that make up the system reactive balance [111]:

i. Generator and rotating units reactive power outputs.
ii. Series reactive power losses in lines, cables and transformers,
iii. Line and cable charging.
iv. Compensation devices such as shunt capacitors and shunt reactors.
v. Consumer reactive power demand.

Even though generator is a main reactive power provider in the power system, however, some other reactive sources like capacitor banks, SVC and STATCOM are also practical options to control power system voltage. Another approach is to make the turns ratio, or tap position, of the transformer adjustable; this is so-called LTC (load tap changing) transformer [111].

Various near-term concentrated options were modeled and tested to find the best technical solution to the Knoxville area voltage problems. The options being tested include the two pairs of 84 MVAR capacitor banks solution, the 300 MVA SVC solution, the 300 MVA STATCON solution and installation of various numbers of D-STATCON devices. As a part of the study, we also tested the solutions of 550, 700 MVA SVC and 550, 700 MVA STATCON and offer a comparison. The concentrated solution options are shown below.

- 84 MVAR capacitor banks at West Hill (bus 524) and Knoxville Primary (bus 458)
- 300, 550, 700 MVA SVC
- 300, 550, 700 MVA STATCON

6.3.2 Capacitor Bank Solution

Mechanically switched shunt capacitor bank (MSC) is the commonly used capacitor banks at the main substations within load center. The function of this kind of capacitor banks is voltage control. Generally, is a shunt-connected, mechanically switched capacitor with no fast dynamic response. MSC can be a part of SVC. In combination with STATCOM kinds of controllers, the fast control is possible. These capacitor banks can be switched in steps to produce a gradual reactive power generation facility [111].

Lower cost and lower loss will achieve by using of MSC rather than SVC or STATCOM. However it lacks of control flexibility and brings more time delay. Currently, MSC is controlled by a micro-processor which monitors system voltage and automatically switches capacitor segments on or off in accordance with system requirements. The main drawback of using capacitor banks compensation equipment in power system is that the reactive power output drops with the voltage squared [111].

Mechanically Switched Capacitor with Damping Network (MSCDN) or C-Type design is also another capacitor bank option, shown in Fig. 6-6. The MSC may influence the network impedance adversely and for this reason a damping circuit may be included. The MSC is now expanded with a damping network called C-Type capacitor. Several configurations exist, but the C-Type filter design is currently the most commonly [96, 97, 98, 112].

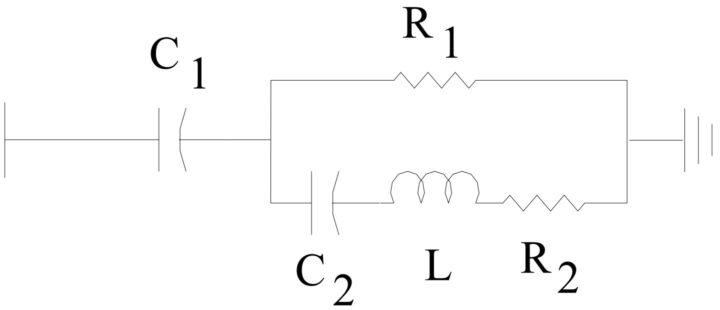


Fig. 6-6. C-type damped MSC topology

There are two pairs of 84 MVAR capacitor banks installed in the Knoxville area system – one pair (totaling 168 MVAR) at Bull Run (bus 94), the other pair at North Knoxville (bus 457). Fig. 6-7 shows this system structure in the research region. Each pair of banks is switched in two stages. The first bank at each location is switched in approximately 0.75 seconds after fault inception, the second at 2.5 seconds after fault inception. The capacitor banks are not switched in ahead of time (i.e. they are not switched in after the first contingency). This ensures that the automatic tap adjustment does not start to compensate for overvoltage when the capacitors switch in, and thus allows the capacitors to have the maximum effect when they do switch in.

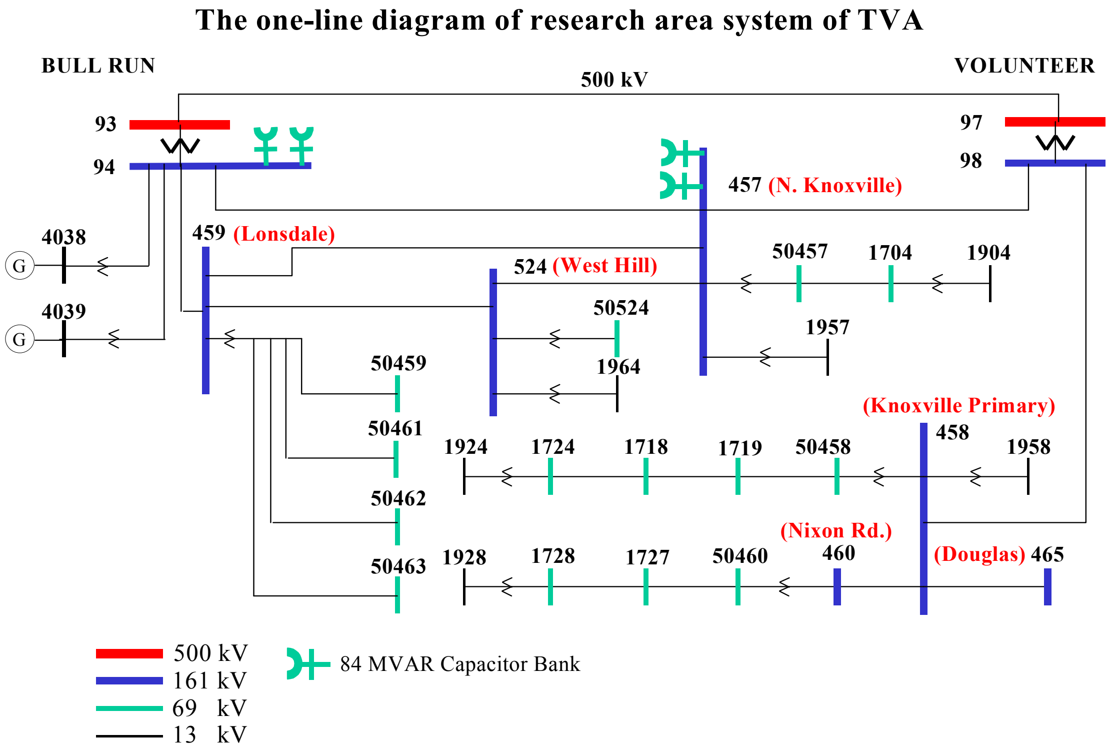
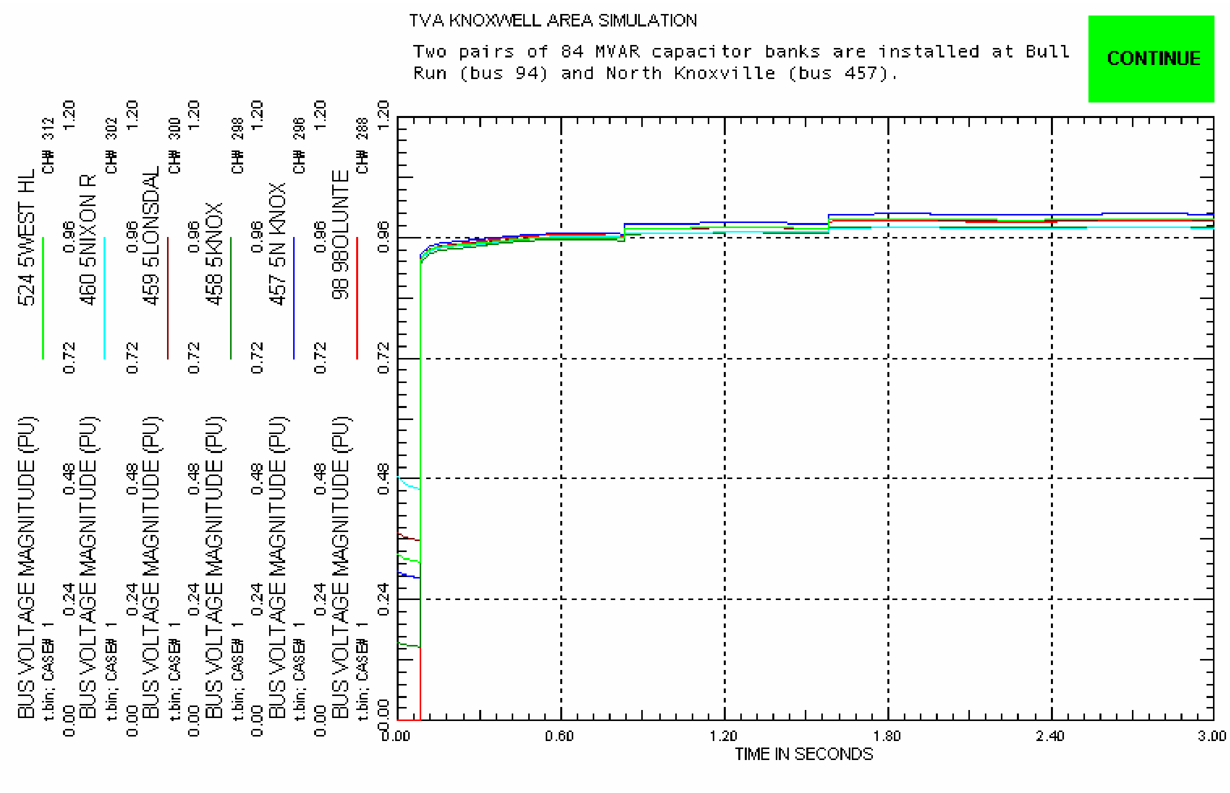


Fig. 6-7. The system structure of the capacitor banks solution

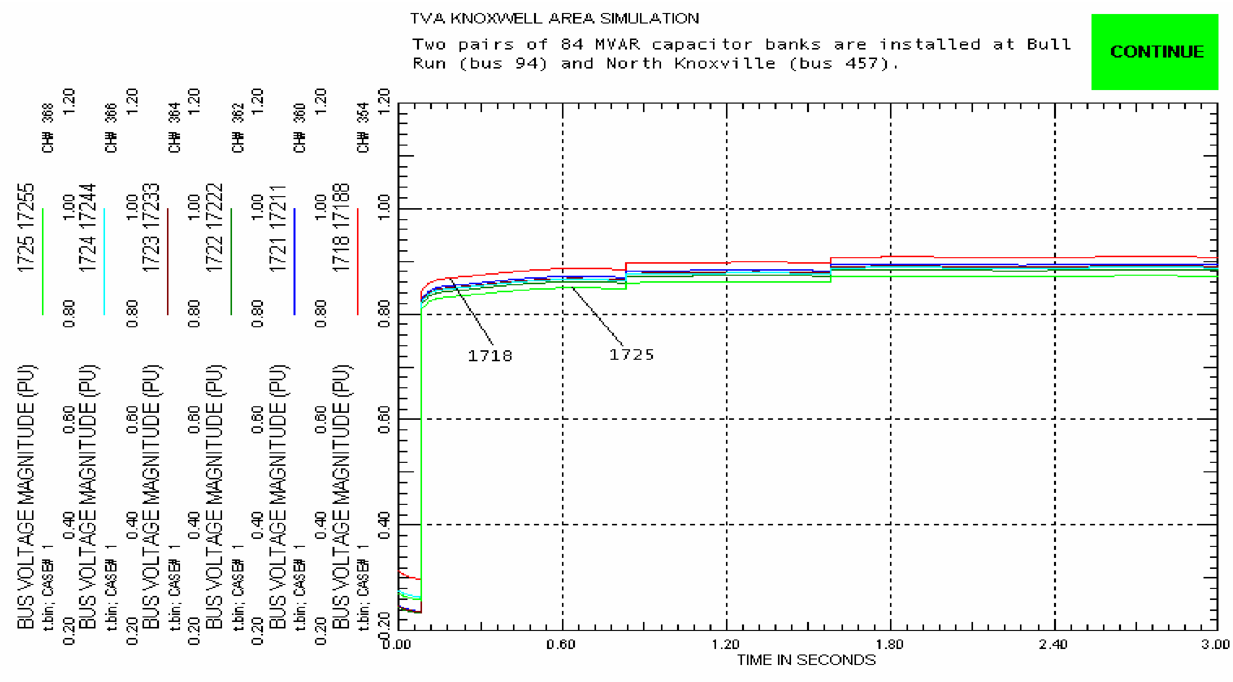
Simulation results are shown in Fig. 6-8 to Fig. 6-10. Fig. 6-8 shows the system 161 kV bus voltage dynamics. After the second capacitor banks connection, 161 kV bus voltage recover to an acceptable level according to WSCC voltage control criteria shown in Fig. 6-2. Fig. 6-9 shows the voltage dynamics of the 6 buses with the lowest final voltage in the 69 kV subtransmission system, whose final voltage are lower than 0.9 pu. Fig. 6-10 shows the voltage dynamics of the 6 buses with the lowest final voltage in the 13 kV distribution system, whose final voltages are above 0.9 pu but lower than 0.95 pu.

From this simulation comparison, we can find the 69 kV sub-transmission network and 13 kV distribution network voltage are lower than the requirement. The voltage in those sub-transmission systems will be the further study focus.



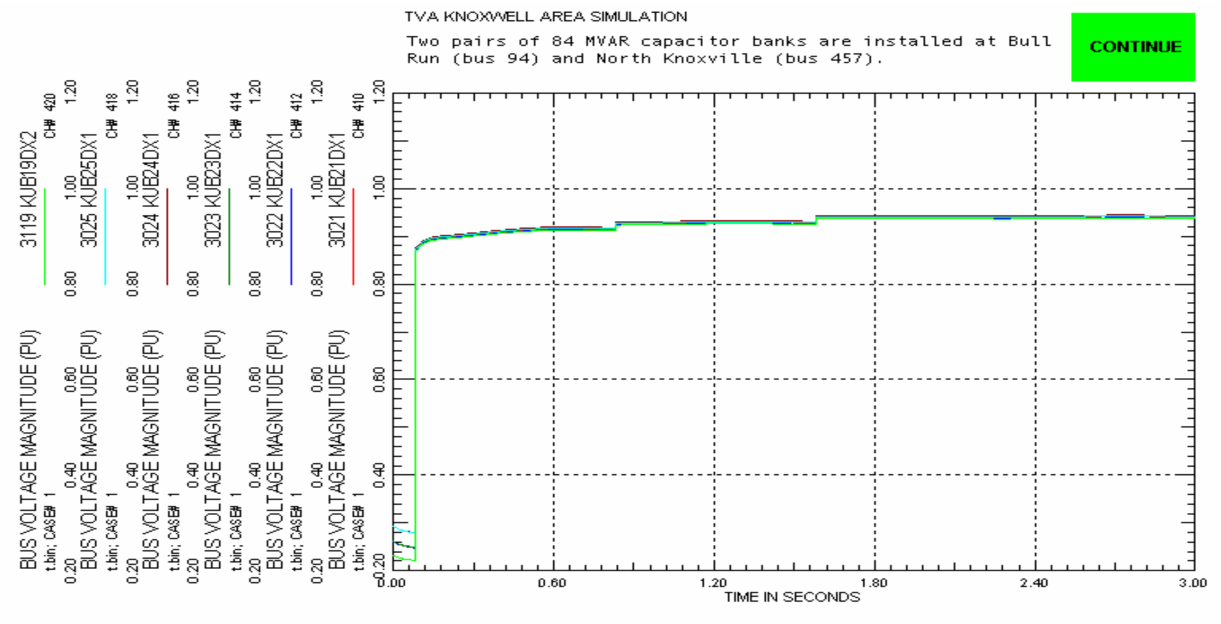
Two pairs of 84 MVAR capacitor banks are installed at Bull Run (bus 94) and North Knoxville (bus 457).

Fig. 6-8. Dynamic voltage in the 161 kV system in Knoxville area. Capacitor banks option



Two pairs of 84 MVAR capacitor banks are installed at Bull Run (bus 94) and North Knoxville (bus 457).

Fig. 6-9. Six buses with the lowest voltage in the 69 kV system in Knoxville area. Capacitor banks option



TVA KNOXWELL AREA SIMULATION

Two pairs of 84 MVAR capacitor banks are installed at Bull Run (bus 94) and North Knoxville (bus 457).

Fig. 6-10. Six buses with the lowest voltage in the 13 kV system in Knoxville area. Capacitor banks option

6.3.3 SVC Solution

According to the IEEE [99] a Static VAr Compensator (SVC) is defined as: a shunt-connected static VAr generator or absorber who's output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage). This is a general term for a thyristor-controlled or thyristor-switched reactor, and/or thyristor-switched capacitor or combination, as shown in Fig. 6-11 [111].

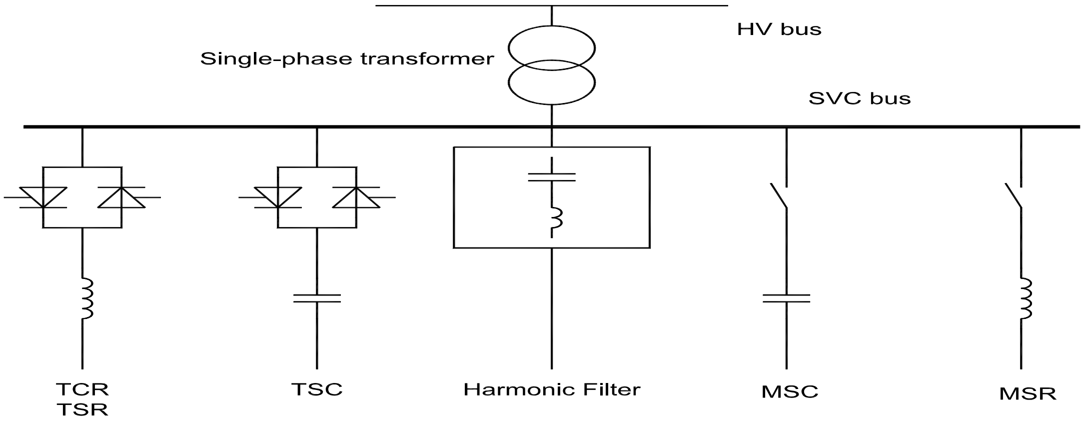


Fig. 6-11. Single-phase line diagram of Static VAr Compensator (SVC) [111]

In a SVC, there are several thyristors controlled separate equipments for leading, lagging var control, including harmonic filters as well. The thyristor-controlled or thyristor-switched reactor is used for absorbing reactive power and thyristor-switched capacitor for supplying leading reactive power. According to [111], SVC applying in power system is usually connected to the high voltage network, with the typical 8-40 kV bus voltage [111].

The V-I characteristic of a SVC is the key factor when determining the required rating and specifying the SVC, shown in Fig. 6-12. The V-I characteristic of SVC has a V-shape because of the use of regular reactors and capacitors, which result the sharp reduction of reactive power support at a large voltage drop. This is the major shortcoming for SVC's application for voltage support in power system during some severe contingencies [111].

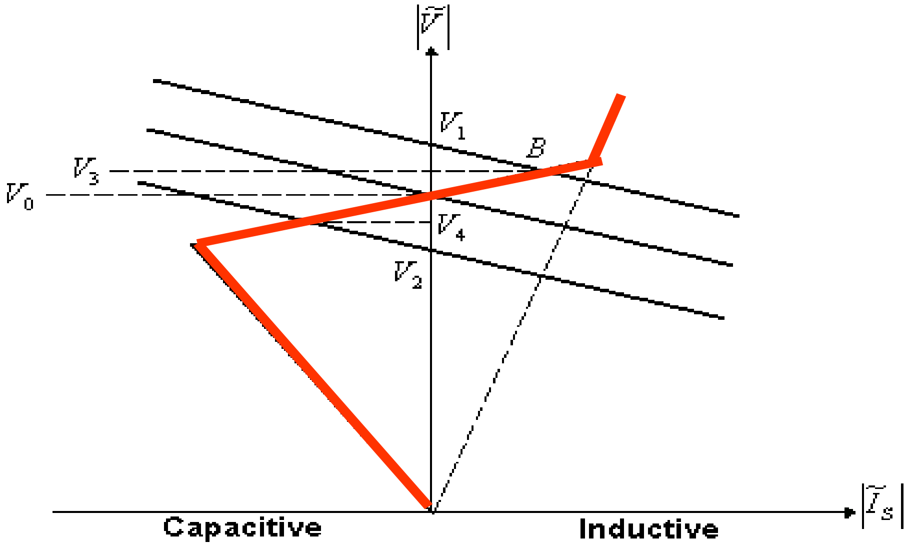


Fig. 6-12. V-I characteristics of SVC [111]

Fig. 6-13 shows the detailed system configuration with SVC at bus 98 (161 kV bus at Volunteer). Fig. 6-14 to Fig. 6-16 are the compensation results for different capacity SVC. SVC with capacity under 550 MVA cannot recover 69 kV sub-transmission system voltage to the acceptable level. Only 700 MVA SVC can almost recover the 69 kV sub-transmission system voltage above 0.9 pu after the most severe contingency. However, 700 MVA SVC will cost huge financial investment from utilities.

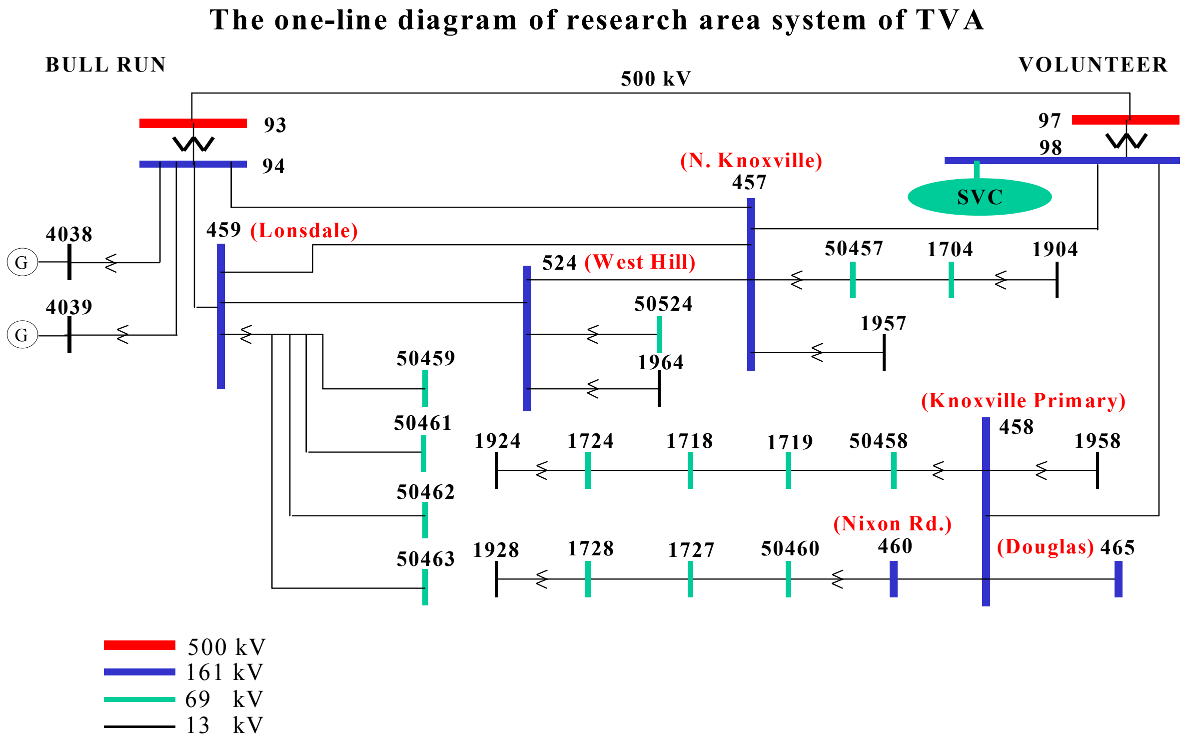


Fig. 6-13. The system structure of the 300 MVA and 550 MVA SVC solutions

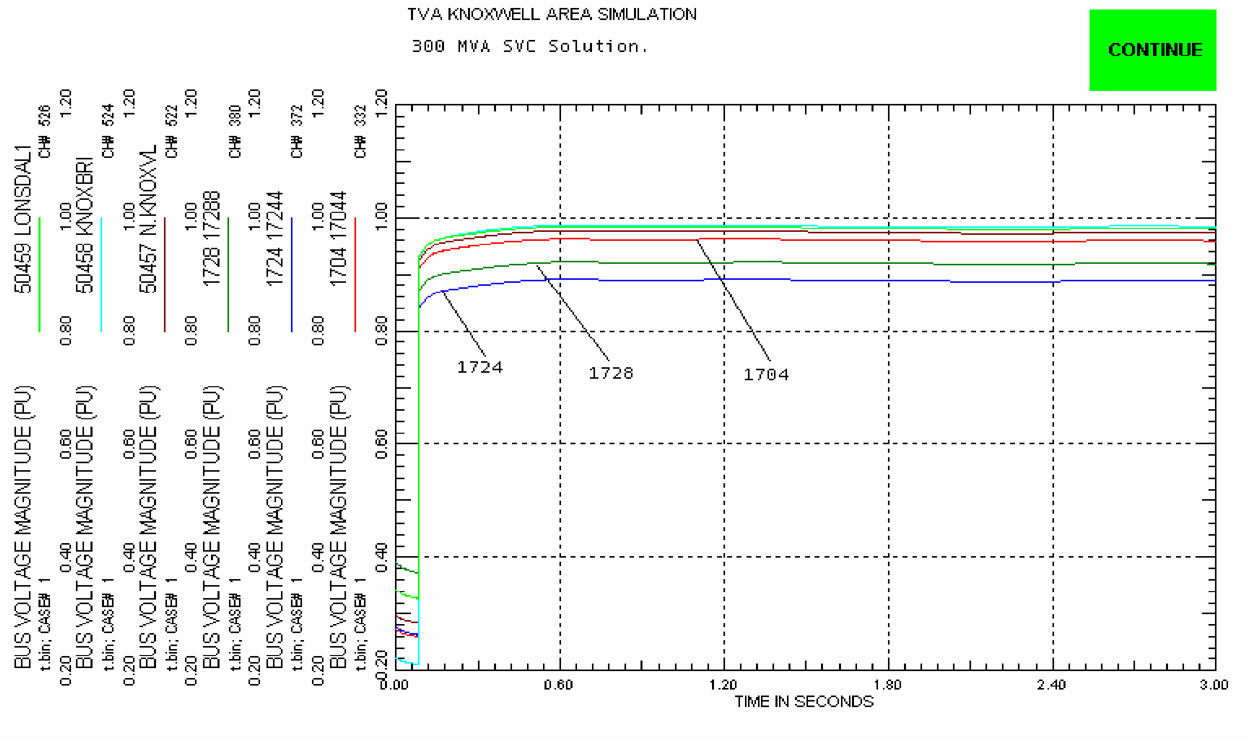


Fig. 6-14. Dynamic voltage of the 69 kV system in Knoxville area. 300 MVA SVC option

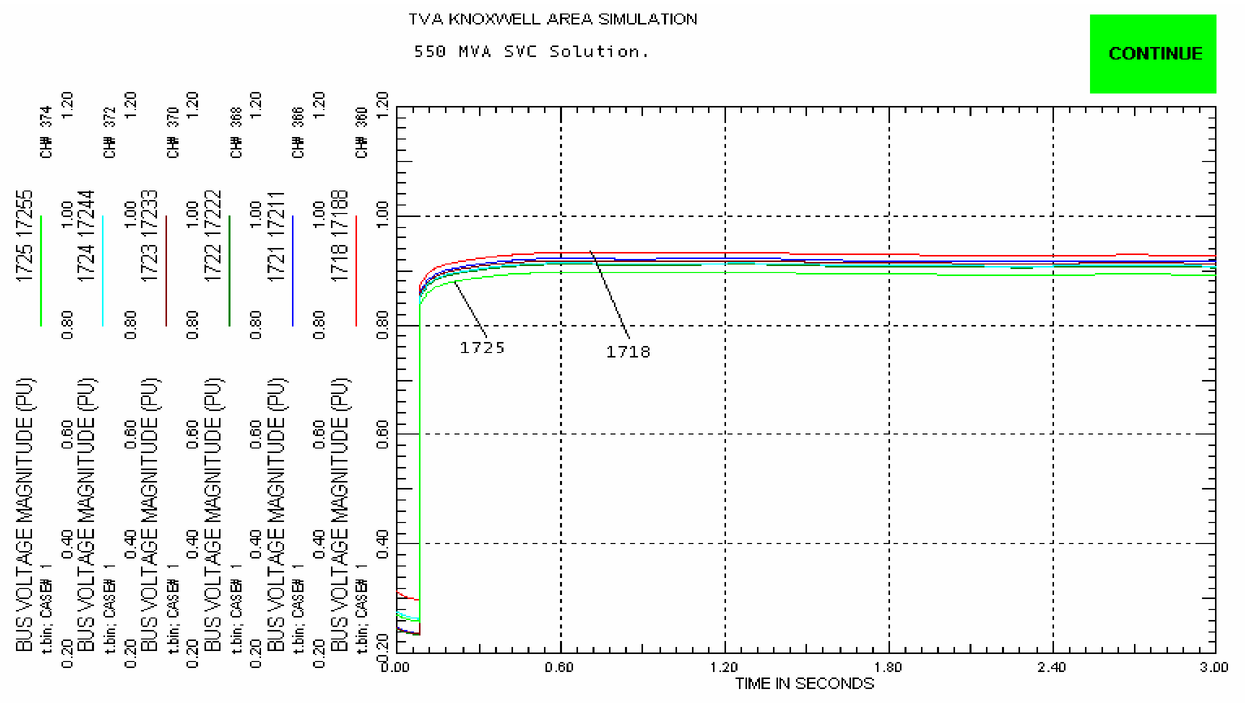


Fig. 6-15. Six buses with the lowest voltage in the 69 kV system in Knoxville area. 550 MVA SVC option

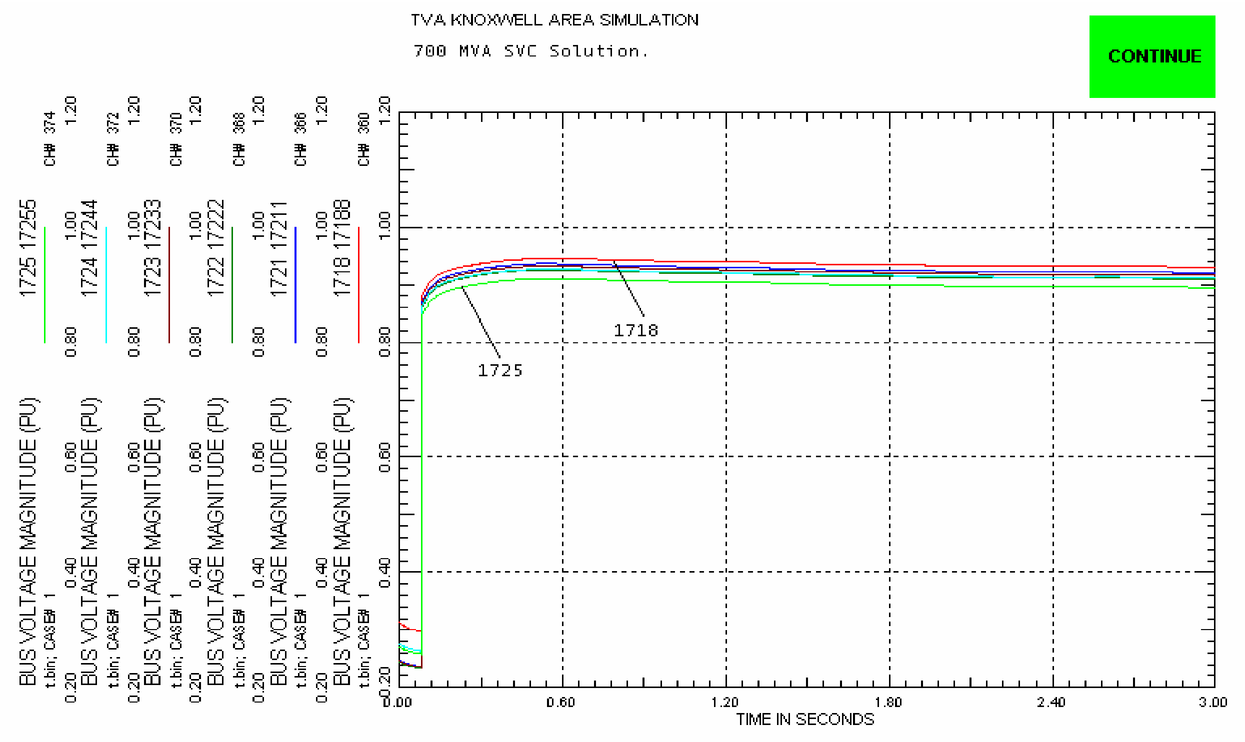


Fig. 6-16. Six buses with the lowest voltage in the 69 kV system in Knoxville area. 700 MVA SVC option

6.3.3 STATCON Solution

According to IEEE [99] a static synchronous compensator—STATCOM is defined as: a static, self-commutated switching power converter supplied from an appropriate electric energy source and operated to produce a set of adjustable multi-phase output voltages, which may be coupled to an ac power system for the purpose of exchanging independently controllable real and reactive power [111].

The STATCOM can provide both capacitive and inductive compensation continuously, which can provide the capacitive current and inductive current independently of the ac system voltage. The V-I characteristic of the STATCOM is shown in Fig. 6-17 [111]. It is important to compare this V-I characteristic of the STATCOM with the V-I characteristics of the SVC. No V-shape characteristics are seen with the STATCOM, with which that STATCOM can provide reactive power at the very low system voltage situation. Therefore, STATCOM is superior to the SVC in providing voltage support in the severe contingencies in power system [111].

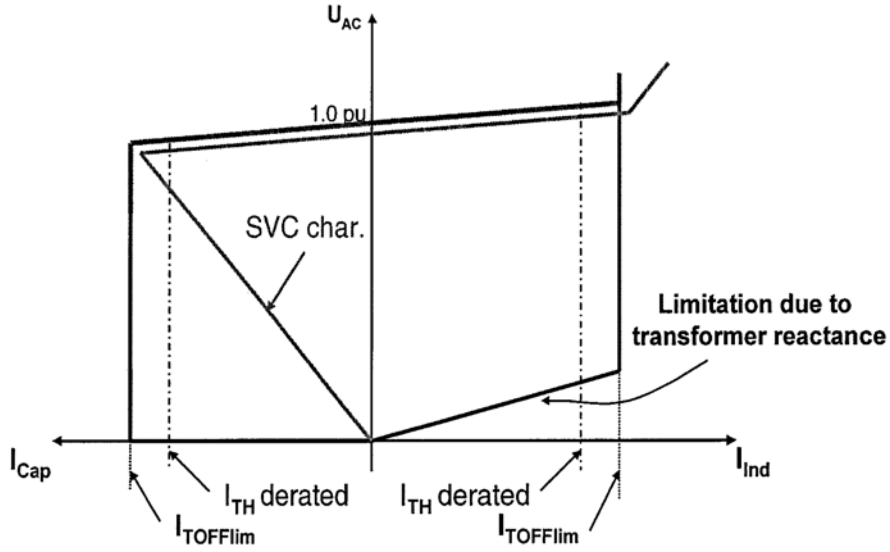


Fig. 6-17. STATCOM V-I characteristics, compared to SVC [111]

In this study, we use STATCOM with 300 MVA, 550 MVA and 700 MVA capacity separately to support the nearby system voltage after contingency. Fig. 6-18 is the detailed one-line diagram of the studied system with STATCOM. Fig. 6-19 to Fig. 6-20 show the simulation results. As can be seen, both 550 MVA and 700 MVA STATCOM can improve the voltage in 69 kV sub-transmission system above 0.9 pu, for which only the 700 MVA SVC can almost achieve.

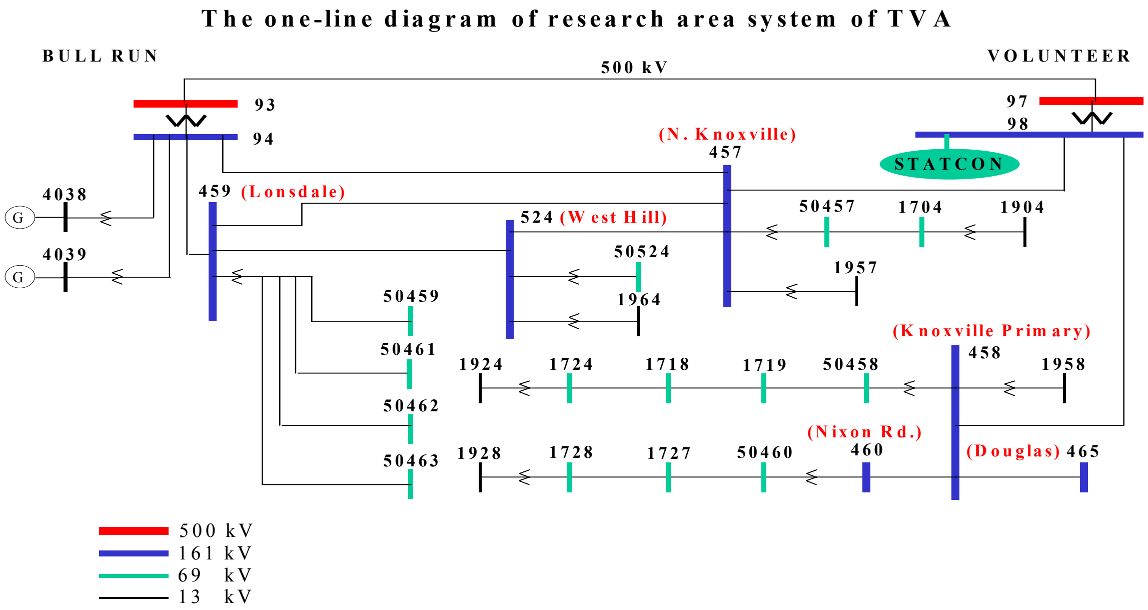


Fig. 6-18. The system structure of the 300, 550 and 700 MVA STATCON solutions

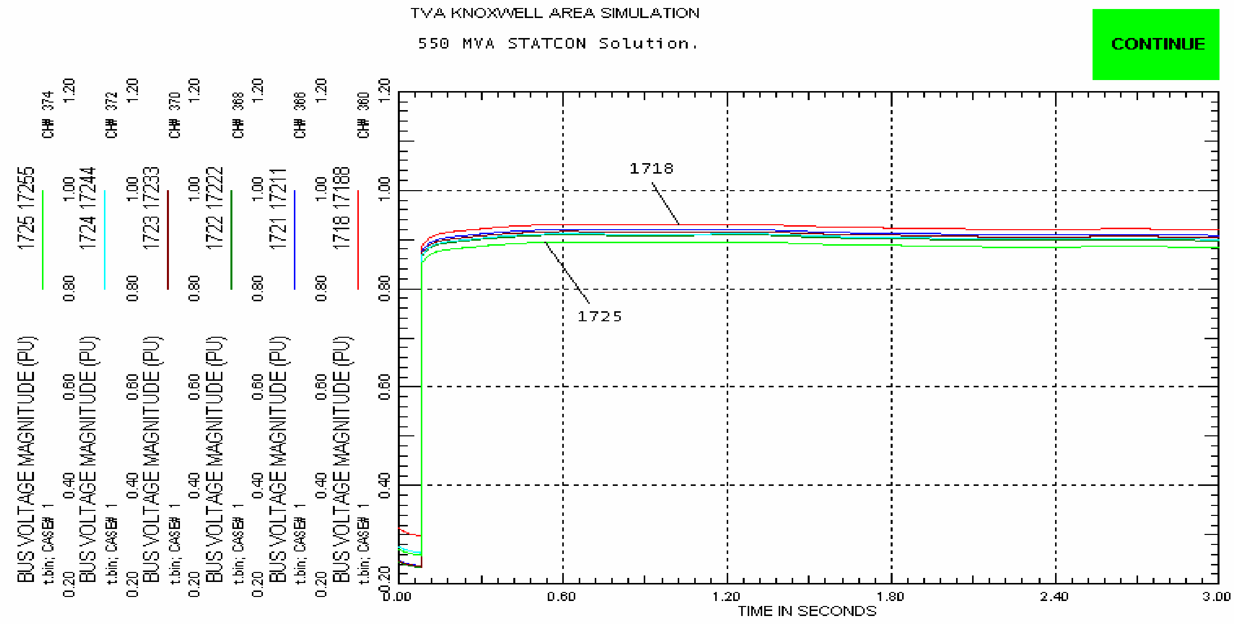


Fig. 6-19. Six buses with the lowest voltage in the 69 kV system in Knoxville area. 550 MVA STATCON option

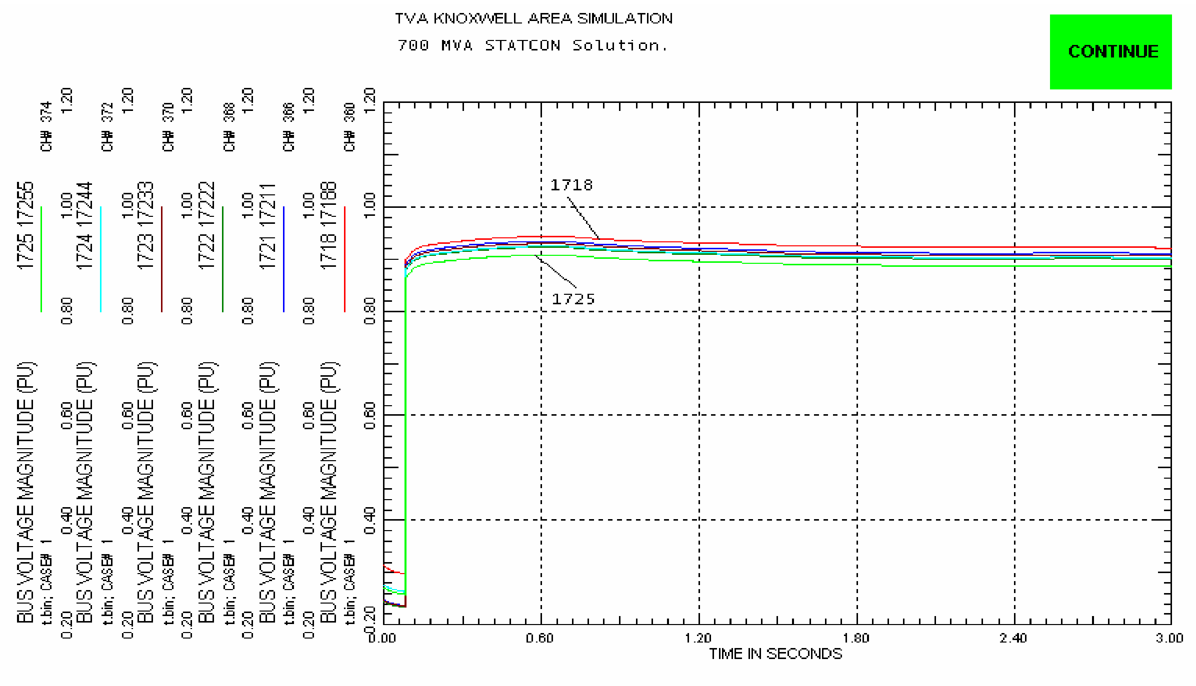


Fig. 6-20. Six buses with the lowest voltage in the 69 kV system in Knoxville area. 700 MVA STATCON option

6.4 Small Distributed FACTS Solution

6.4.1 Distributed FACTS Technology

Being an example of a small distributed FACTS technology, D-STATCOM can operate in two modes:

- Current Control: In this mode the DSTATCOM acts as an active filter, power factor corrector, load balancer, etc. These functions are called the load compensation.
- Voltage Control: In this mode the DSTATCOM can regulate a bus voltage against any distortion, sag/swell, unbalance and even short duration interruptions.

6.4.2 Available Distributed FACTS Devices

Currently, the popular commercial distributed FACTS devices are produced by American SuperConductor company and S & C company. They are distributed SMES (or D-SMES) and dynamic VAR system (or D-VAR) produced by America SuperConductor. The products of S &

C are PureWave D-STATCOM and Adaptive VAR compensator (AVC) [108, 109].

Superconducting Magnetic Energy Storage (SMES) system is a device for storing and instantaneously discharging large quantities of power. D-SMES is a shunt connected Flexible AC Transmission (FACTS) device designed to increase grid stability, improve power transfer, and increase reliability. Unlike other FACTS devices, D-SMES injects real power as well as dynamic reactive power to more quickly compensate for disturbances on the utility grid. Fast response time prevents motor stalling, the principle cause of voltage collapse.

Dynamic VAR system (D-VAR) detects an instantaneously compensate for voltage disturbances by injecting leading or lagging reactive power at key points on power transmission grids. D-VAR systems help alleviate voltage problems in many applications including reactive compensation in transmission and distribution systems, steady state voltage regulation in long radial delivery systems, wind farms, increasing grid capacity in transmission systems, and voltage sag mitigation at large industrial facilities.

PureWave DSTATCOM is a solid-state, reactive power source that provides flexible voltage control for transmission and distribution system. It provides leading or lagging VARS within ¼ cycle to improve line capacity utilization, shorten voltage recovery time, and minimize energy losses. The PureWave DSTATCOM protects the utility transmission or distribution system from voltage sags and/or flicker caused by rapidly varying reactive current demand. In utility applications, a DSTATCOM provides leading or lagging reactive power to achieve system stability during transient conditions. The DSTATCOM can also be applied to industrial facilities to compensate for voltage sag and flicker caused by non-linear dynamic loads, enabling such problem loads to co-exist on the same feeder as more sensitive loads.

PureWave AVC Adaptive VAR Compensator is an economical, distribution-class VAR compensator that addresses the reactive-power management requirements of a variety of dynamic loads. This microprocessor-controlled device utilizes power-electronic switches to instantaneously insert the appropriate number of multi-stage power capacitors, providing 300 kVAR or more of reactive compensation on a cycle-by-cycle basis. The PureWave Adaptive

VAR Compensator provides real-time voltage support for voltage sags and dips caused by rapidly-changing dynamic loads, as well as flicker mitigation and power-factor correction. System stability increases by reducing voltage fluctuations and managing reactive power flow.

6.4.3 Evaluation by Dynamic Analysis

In this study, we select eight 8 MVA distributed STATCOM installed in different voltage level (161 kV and 69 kV) network to justify the compensation effects of those distributed FACTS devices.

Eight 8 MVA D-STATCON at 161 KV Level

Eight 8 MVA distributed STATCOM are installed in the 161 kV system with one pair at each location, which is shown in Fig. 6-21. The voltage dynamics of the 69 kV buses with the lowest voltage are shown in Fig. 6-22. As can be seen, some 69 kV sub-transmission system bus voltage cannot recover above 0.9 pu. The control result is not ideal.

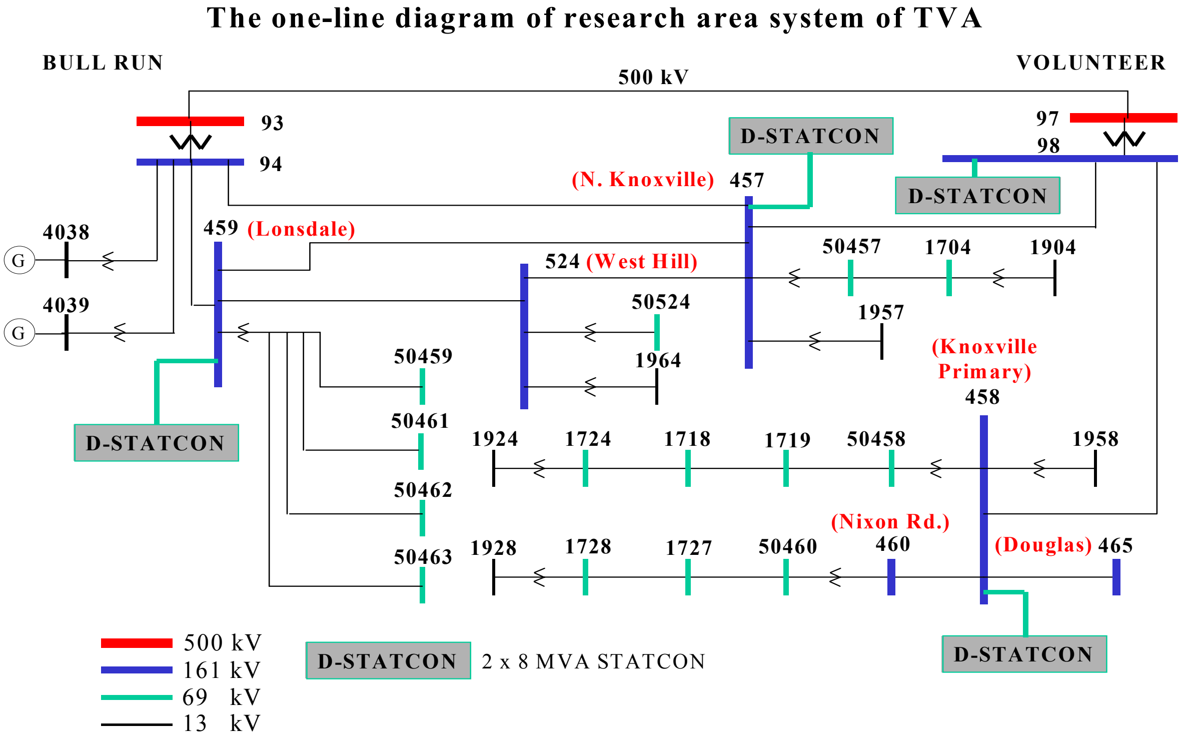
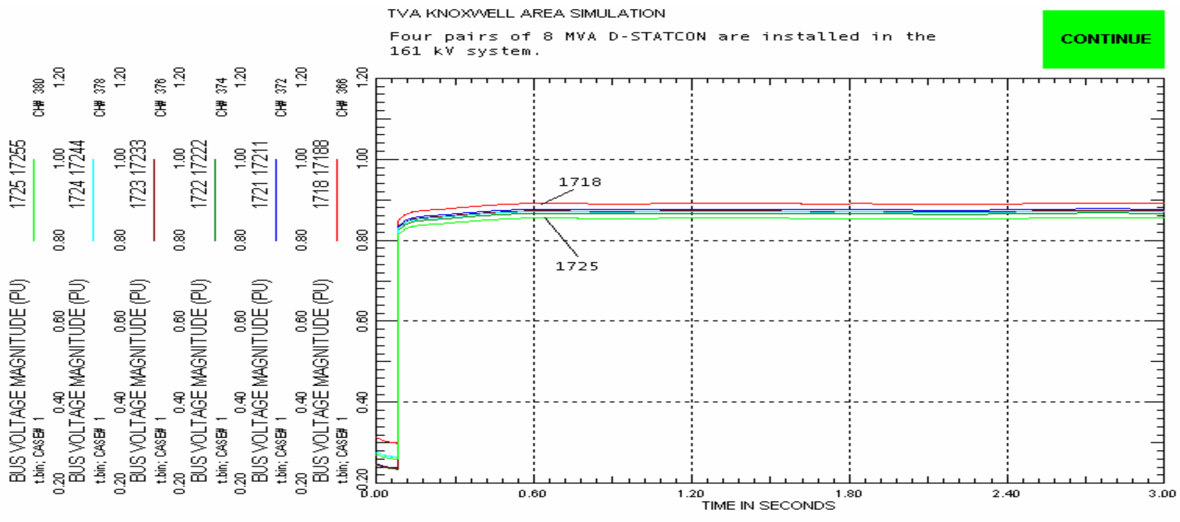


Fig. 6-21. The system structure of the D-STATCON solution (161 KV level)

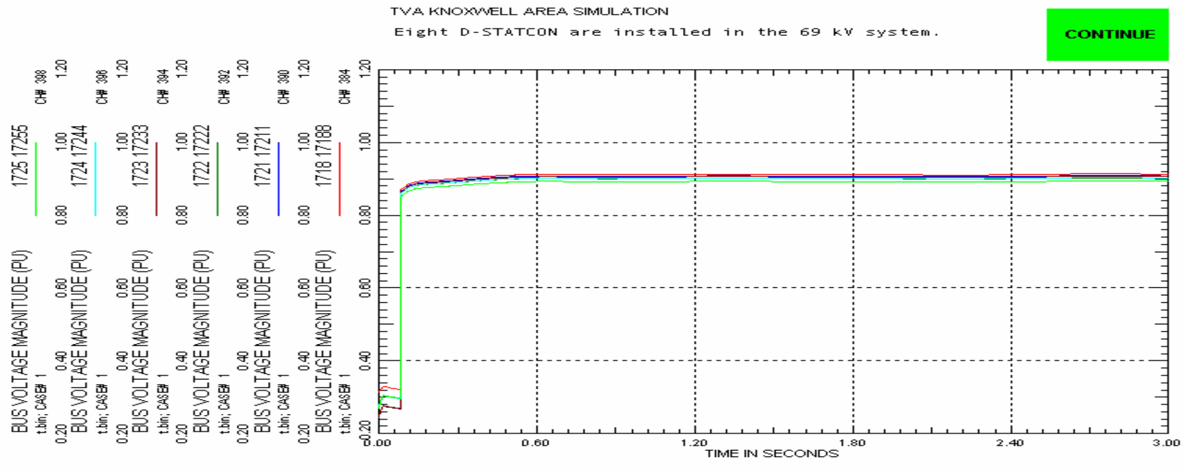

TVA KNOXWELL AREA SIMULATION

Four pairs of 8 MVA D-STATCON are installed in the 161 kV system.

Fig. 6-22. Six buses with the lowest voltage in the 69 kV system in Knoxville area. D-STATCON (161 kV) option

Eight 8 MVA D-STATCON at 69 KV Level

As shown in the previous simulation results, all the above options cannot improve the voltages of some buses in the 69 kV system in Knoxville area to the acceptable level (0.90 P.U.). The option of D-STATCON installed in the 69 kV system maybe a better choice to solve this problem, because the D-STATCON installed in the 69 kV system will improve directly the voltage in this voltage level system. Eight 8 MVA D-STATCON are installed at bus (1718, 1721, 1722, 1723, 1724, 1725, 1726, 1728) with the lowest voltages with their voltage. Fig. 23 shows the compensation result. The voltage of those buses is above 0.9 P.U.


TVA KNOXWELL AREA SIMULATION

Eight D-STATCON are installed in the 69 kV system.

Fig. 6-23. Six buses with the lowest voltage in the 69 kV system in Knoxville area. D-STATCON (69 kV) option

6.5 Under Voltage Load Shedding

There are two basic power system control concept: preventive control and remedial control. The under voltage load shedding (UVLS) control is a remedial control, which means the process of voltage collapse has begun, or is about to begin, and the objective of UVLS is to regulate the instability mechanisms to avoid system degradation. UVLS has been implemented by several utilities already as a final defense method to avoid voltage collapse.

6.5.1 Under Voltage Load Shedding Concept

UVLS is an effective (technically and economically) control-based measure to prevent voltage instability and collapse for operating conditions and disturbances that have a low probability of occurring. UVLS provides fast, controlled, reliable, and predictable load shedding. It eliminates the delays and unpredictability of conventional UVLS and removes the burden from the system operators who would otherwise be forced with the impossible task of shedding load to avoid voltage instability [94, 95].

The automatic under voltage load shedding scheme monitors a selected list of dynamic system conditions and will shed load until proper system voltages and var reserves are restored. An UVLS scheme is generally applied as “safety net” measure in situations where voltage collapse is anticipated and can potentially result in blackout conditions. UVLS is usually initiated after exhausting all other counter-measures in attempting to arrest a voltage collapse condition.

Three main areas for consideration in a UVLS scheme:

- The amount of load to be shed
- The timing of the load shedding event
- The location where load is to be shed

An UVLS scheme may be applied as an economically viable measure to bridge the gap resulting from the identification of the transmission reinforcement need to the actualization of that need. An UVLS scheme has generally been employed as a low-cost measure to avert voltage instability due to extreme contingencies. Alternatives to improve reactive margin and voltage profile in a voltage sensitive area include new generation, new transmission facilities, and shunt compensation including VAR compensation. For low probability events and extreme contingencies, UVLS may be the most economical solution in preventing voltage collapse.

6.5.2 UVLS Design Guidelines

Electric systems experiencing severe disturbances and with heavy loading on transmission facilities can be vulnerable to voltage collapse. A coordinated undervoltage load shedding program can be employed in preserving the security of a generation and transmission system in the event of system disturbances. Such a program is useful to minimize the risk of total system collapse, protect generating equipment and transmission facilities against damage, provide for equitable load shedding among load-serving entities, and improve overall system reliability [94, 95].

Undervoltage load shedding schemes should be coordinated with other system measures used to disconnected load, such as remedial action direct load tripping. Automatic undervoltage load shedding can be sued within large areas that have strong transmission systems as a guard against voltage collapse in the event that multiple contingencies and extreme conditions should occur. When applied to low probability, multiple contingency events, undervoltage load shedding provides a low-cost means of preventing widespread system collapse.

The following points should be kept in mind while designing the UVLS schemes [94, 95]:

1. Load shedding scheme should be designed to coordinate with protective devices and control schemes for momentary voltage dips, sustained faults, low voltages caused by stalled air conditioners, etc.
2. UVLS relays must be on PTs that are connected above automatic LTSs.
3. Voltage pick-up points for the tripping signal should be set reasonably higher than the "nose point" of the critical P-V or Q-V curve.
4. Voltage pick-up points and the time delays of the local neighboring systems should be checked and coordinated.
5. Redundancy and enough intelligence should be built into the scheme to ensure reliable operation and to prevent false tripping.

6. Enough load should be shed to bring voltages to minimum operating voltage levels or higher. Maintain VAR margin according to WSCC's Voltage Stability Criteria.

Generic load shedding schemes will not be suitable for every area within all the power system. It should be a case on case study. Therefore, the methodology presented in Fig. 6-24 here is very basic and applies to almost all load shedding schemes. Customizing of individual schemes can be done after the basic analysis is completed.

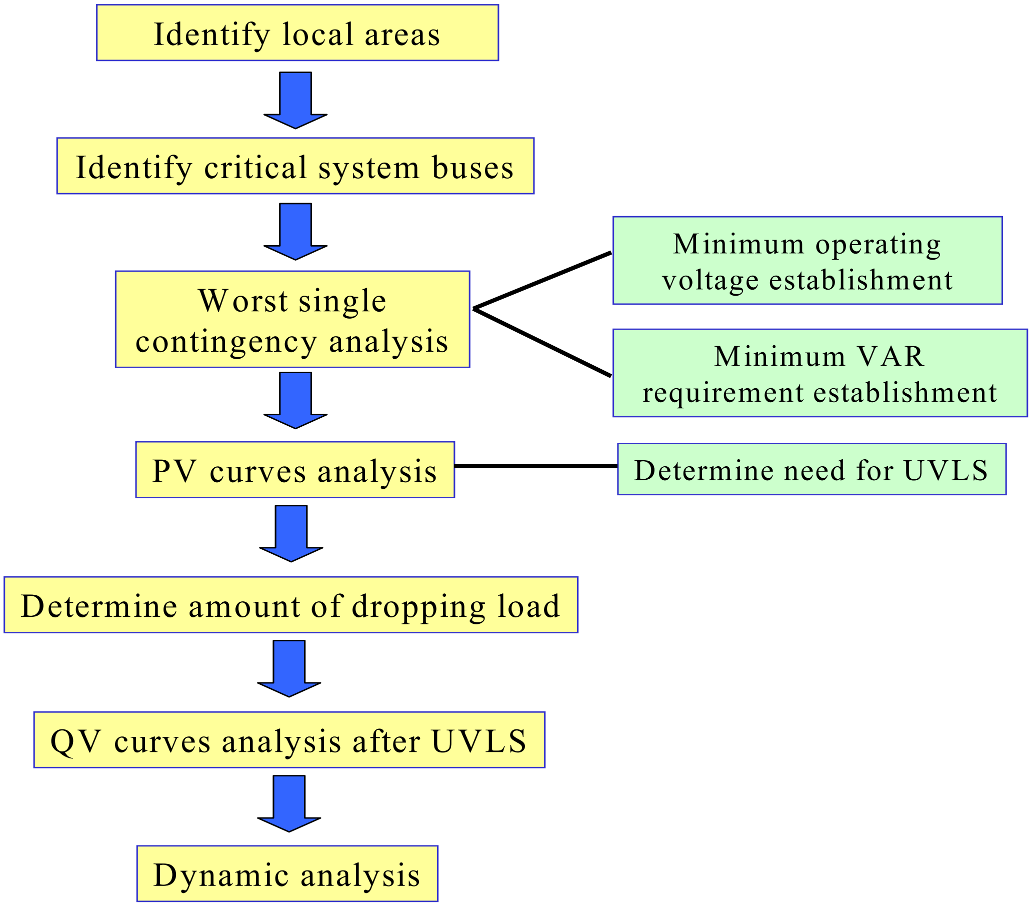


Fig. 6-24. General UVLS design methodology

Followings are the existing or planned UVLS schemes [101-107].

- Pacific Gas & Electric Company Fresno undervoltage load shedding scheme (Ashlan, Mccall, Figarden substations)
- Boise Bench C-231 capacitor RAS control and undervoltage load shedding program

- Sacramento Valley UVLS program
- Procedures for the EPE undervoltage load shedding scheme
- BPA PUGET SOUND undervoltage load shedding scheme
- Hydro-Quebec system undervoltage load shedding scheme
- Public Service Company of New Mexico UVLS scheme
- Entergy Services Inc. undervoltage load shedding scheme
- Saudi Arabia UVLS scheme

6.5.3 UVLS Design for the Study Area System

By the analysis of studied area power system and the applied UVLS schemes used by other utilities, fast UVLS, which can be as fast as 1 to 1.5 seconds like BPA scheme, can be a practical approach to prevent wide spread voltage collapse or blackout. This UVLS scheme should be a technically-effective and economically-viable control-based under voltage load shedding scheme. Many factors, like generator and transmission line status, should be considered in the decision logic. Some main points should be considered during the UVLS design. Before the final scheme design, following questions should be answered. Fig. 6-25 shows the draft UVLS scheme designed for the studied area system.

- What are the consequences of operating below normal voltages for tens of seconds or minutes?
- How much of the UVLS should be fast?
- What percent of the total load should be shed by UVLS?
- What is the highest practical time undervoltage relay setting?
- How advantage are new type voltage relays?
- What special monitoring facilities should be provided?
- How should load restoration be accomplished?

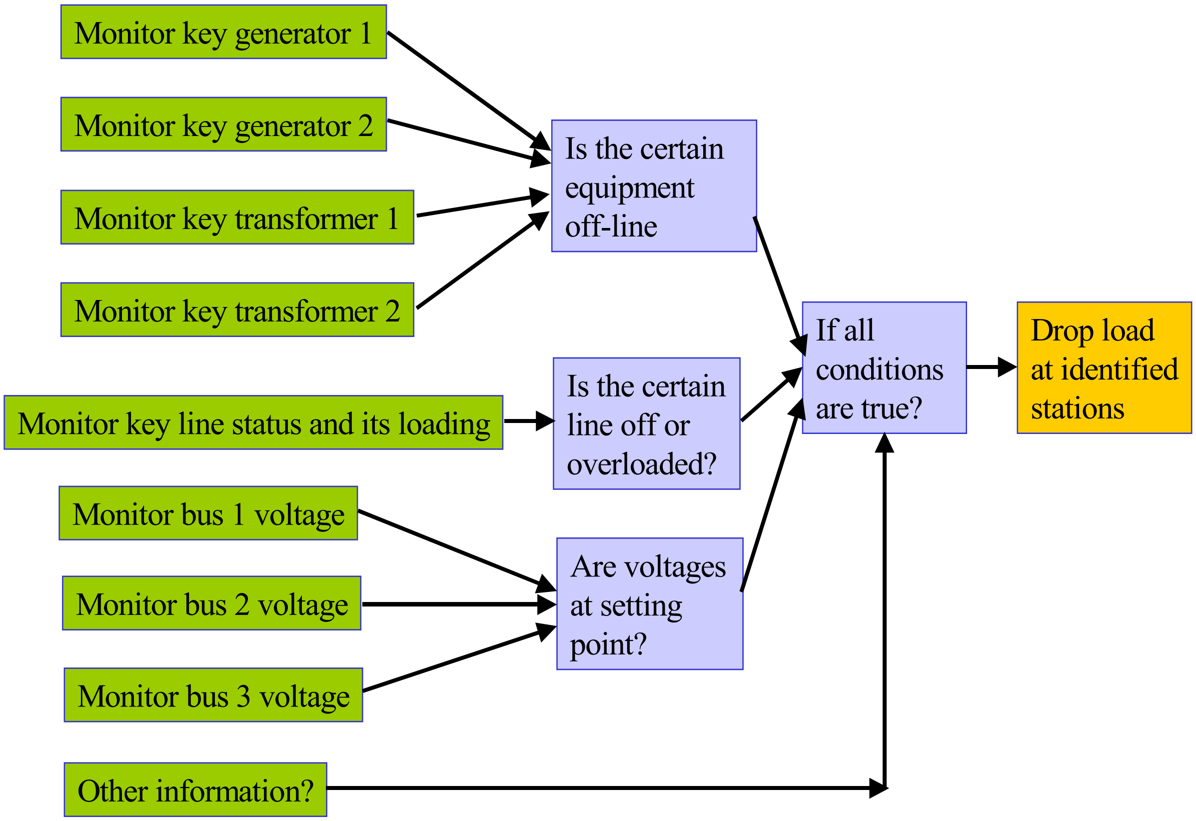


Fig. 6-25. Draft of the proposed UVLS scheme for the studied system

6.6 Summary

The study in this chapter is based on a real voltage problem in the Knoxville area in TVA system. This area has the low voltage problem for certain contingencies and potential voltage collapse for severe contingencies. Based on steady state analysis and dynamic analysis, special low voltage in the 69 kV subtransmission system was identified.

Several voltage and reactive power control options were addressed to solve the problem, which includes mechanical switching capacitor banks, SVC, STATOM and distributed STATCOM solutions. The study results show that the distributed STATCOM solution is the best way to solve the low subtransmission system voltage within the wide area. UVLS study was conducted as the final defense to avoid the happening of voltage collapse.

Chapter 7. Conclusions and Future Work

The electric power supply industry, with its humble beginning in the 1880s, has evolved into one of the largest industries. Secure and reliable operation of the electric power system is fundamental to national and international economy, social security and quality of modern life, because electricity has become a basic necessary in modern society. The domestic power industry has gone through many changes in the past several years and continues to evolve. The major trends in the power industry include deregulation, ownership concentration of generation and transmission, limitation of transmission expanding, environmental issue restriction, and more influence from electric consumers.

The complicated power grid is now facing severe challenges to meet the high level secure and reliable operation requirements, which include lack of transmission capability, restraints by a competitive market environment, and power infrastructure vulnerability. Many blackouts happing in the year 2003 all over the world indicated the severity of those challenges.

The bright side is that a wide range of new technologies will play a major role in helping today's electric power industry to meet the above challenges. Those technologies will shape the future directions of power industry. These technologies fall in a wide range of category like material science, monitoring, analysis tools, control, next generation, distributed resources, information system and intelligent devices. Those new technologies will provide necessary capabilities when combined in an over-all system design. This dissertation has focused on some key technologies among them, including the emerging technologies of energy storage, controlled power electronics and wide area measurement technologies. Those technologies offer an opportunity to develop the appropriate objectives for power system control.

In bulk power transmission systems, the use of power electronics based devices, which is represented mainly by FACTS devices, can potentially overcome limitations of the present mechanically controlled transmission system. These flexible networks help delay or minimize the need to build more transmission lines and enable neighboring utilities and regions to economically and reliably exchange power. Integrating an energy storage system (ESS), such as battery energy storage systems (BESS), superconducting magnetic energy storage (SMES), flywheel energy storage, or supercapacitor energy storage, into a voltage source converter (VSC)-based FACTS device can lead to improved controller flexibility by providing dynamic decentralized active power capabilities. Combined FACTS/ESS can improve power flow control, oscillation damping, and voltage control easily and economically. Considerable attention has been given to developing control strategies for a variety of VSC-based FACTS devices to mitigate a wide range of potential bulk power transmission problems. While the FACTS/ESS combination has been proposed in theory, the development of FACTS/ESS has lagged far behind that of FACTS alone, thus a comparable field of knowledge for FACTS/ESS is sparse.

Energy storage systems can provide value added benefits to improve stability, power quality, and reliability of power systems. Many electric utilities in the U.S. are beginning to implement energy storage systems (ESS) into their existing FACTS devices or install new energy storage systems for many different applications. However, there is a significant lack of scientific mechanisms to guide their technical decision making process. The study in this dissertation has culminated in a comprehensive set of guidelines and metrics for the implementation of FACTS/ESS in bulk power systems.

The interest of this study lies in a wide range of FACTS/ESS technology applications in bulk power system to solve some special problems that were not solved well without the application of FACTS/ESS. The special problems we select to solve by using FACTS/ESS technology in this study include power quality solution by active power compensation, electrical arc furnace (EAF) induced problems solution, inter-area mode low frequency oscillation suppression, coordination of under frequency load shedding (UFLS) and under frequency governor control (UFGC), wide area voltage control, etc.

From this study, the author of this dissertation reveal the unique role that FACTS/ESS technology can play in the bulk power system stability control and power quality in power system. In this dissertation, almost all the studies are based on the real system problems, which means that study results are special valuable to certain utilities that have those problems.

By the theoretical and fundamental research in this study, we have achieved thorough understanding of power system responses to dynamic active power injection/absorption, comprehensive characterization of different energy storage technologies with the corresponding power electronic interfaces, comparison of different storage systems with respect to typical applications. The study in this dissertation can assist power industry choose the right FACTS/energy storage technology for their intended functions, which will improve the survivability, minimize blackouts, and reduce interruption costs through the use of energy storage systems.

One of the important and fundamental topics of FACTS/ESS applications is the impact of active power compensation. The questions of the role of active power compensation in power system and the difference between active power compensation and reactive power compensation should be answered. It is easily understood that reactive load can cause power quality problems associated with voltage. In our study, we find that the real load can not only cause the voltage drop but also the angle variation at some critical buses in power system. These phase angle variations and active power fluctuations can bring stability problems in the bulk power systems. Even the shaft angle of the generators in the nearby system oscillates because of the pulsing active load. That could be harmful to the generator shaft and may reduce the life of generator dramatically. In this dissertation, we studied the impact of active load, by using the pulsing active load as an example, on the bulk power system. The tradition reactive power controllers like SVC and STATCOM cannot solve fully those problems caused by active load. Advances in both energy storage technologies and the necessary power electronics interface have made energy storage systems (ESS) a viable technology for high power utility. ESS makes it as a possibility to use active power compensation in solving the power quality problems caused by active load. The study in this dissertation proved that FACTS/ESS is a good controller to solve the power quality problems induced by both active and reactive load.

X/R ratio is very important when we study the effect of active and reactive load on the voltage and angle fluctuation in the system. The voltage effect of active power drawn by an EAF is reflected by the real part of system impedance (Thevenin Impedance) R_n. A very common mistake is to assume that in the power system, the X/R ratio is large enough to omit the voltage drop caused by the active power of the EAF. An incorrect approach to calculating X/R ratio is by considering only the upper transformer or branch. Using this approach one will certainly arrive at a X/R of over 10. The correct approach is by looking at all of the parameters including the load. In other words, the R and X are not proportional to the impedance of the upper transformers and lines; instead they should be the Thevenin Impedance seen from the PCC bus of the entire system. Based on the study in this dissertation, the X/R ratio in a bulk power system is not large enough to omit the effect of active load. From the simulation results in this study, we can see that the active load plays an important role on the bus voltage drop.

In this dissertation, we also studied the solution of power quality problems induced by electric arc furnace by FACTS/ESS. Several studies reported voltage flickers from the operation of an EAF on the power feeders in nearby factories. The studies also discovered that the neighboring distribution network inherently resonated an active oscillation. As mentioned above, instantaneous fluctuations with large amplitudes of active and reactive power in EAF's are sources of power quality disturbances in an electric power system. Many earlier studies have shown that the pulsing load in an EAF could be very harmful to the generator shaft and may reduce the life of generator dramatically. Dynamic active power compensation as offered by FACTS with ESS can offer good solution as shown by the study results in this dissertation.

Low frequency oscillations in some parts or between parts of the interconnected power systems are commonly experienced, which remains as an main threat to power system stability. The low frequency oscillations take place as synchronous generators swing against each other. The frequency range of these oscillations is from 0.1 to 2.5 Hz, related to the dynamic power transfer between areas. In this dissertation, the inter-area mode power system low frequency oscillation happened in Nashville area of the TVA system has been analyzed. This oscillation is an inter-area mode oscillation. There are 4 groups of generators at 4 different locations within this area. Generators swing against those in other groups. In each group, generators do not swing against each other, having the same dynamic trends. Both the concentrated and distributed FACTS/ESS solutions options were studied. The active and reactive power controls of D-FACTS/ESS are independent. The active power of D-FACTS/ESS is controlled to damp the local low frequency oscillation. Reactive power of D-FACTS/ESS is controlled to keep the local voltage at a standard level. The results show that better control result will be achieved when adequate capacity devices are used.

One of the most undesirable conditions for power system operation is the loss of generator units or transmission lines causing big power-load unbalance. This kind of unbalance will cause the drop of power system frequency from its steady state. If not properly counteracted, it can lead to major stability problems. The typical protection scheme for such conditions is under frequency load shedding (UFLS) to stop the frequency drop after generation-load unbalance happens. In most severe generation-load unbalance conditions, the frequency drops so quickly that the governor cannot fully activate spinning reserve. Most of the time, UFLS serves as a final defense tool to prevent the system collapse before governor, which is called under frequency governor control (UFGC) can fully activate spinning reserve quickly enough to restore the system to its normal operating frequency. This may results in over-shedding. UFLS happens before UFGC has the time to take full action. Both the over shedding and unfully used of spinning reserve mean the loss of big amount of money both to utilities and power consumers. Unfortunately, no method exists to coordinate these two functions before the study in this dissertation. The application of SMES or D-SMES can provide a direct way to coordinate the UFLS and UFGC. It can help to fully activate the system spinning reserve, which can prevent over shedding. The application of SMES or D-SMES can coordinate the UFGC and UFLS to achieve the goal of full activating the spinning reserve and minimizing shedding load. The active and reactive power controls of SMES are independent. The active power is controlled to stop the dropping of system frequency and the reactive power is control to stabilize the local voltage. The research results show that SMES or D-SMES can slow the quick drop of system frequency and hold for the full activation of system spinning reserve. That can help the governors output their maximum reserve before UFLS drops more load which results in minimized load shedding.

In this study, the steady state analysis and dynamic analysis of the voltage problems as well as the control options of the Knoxville area system of TVA were also studied. Various near-term options were modeled and tested to find the best technical and economic (we will discuss it lately) solutions solving the Knoxville area voltage problems. The options include two pairs of 84 MVAR capacitor banks solution, 300 MVA SVC solution, 300 MVA STATCON solution and installation of various numbers of D-STATCON devices. We also tested the solutions of 550, 700 MVA SVC and 550, 700 MVA STATCON solutions. Using all the centralized compensation methods mentioned above, the voltage of 69 kV subtransmission system and 13 kV distribution system cannot be improved to the acceptable level. Their values are less than 0.95 P.U. at the final steady state. It should be much more concerned for the voltage control of the Knoxville area system of TVA. Unlike the active power, the reactive power should not be transmitted over a long distance. Load center voltage levels can only be controlled by nearby reactive power sources. For the large and complicated system such as TVA, the distributed compensation is a preferable option. For the complicated network structure of the research region system, the D-STATCON will play a better role in solving the low voltage problems of the 69 subtransmission and 13 kV distribution systems. But the size and location of the D-STATCON require more detailed study.

As we mentioned in Chapter 1 in this dissertation the range of the FACTS/ESS applications in bulk power system is large. The content in this study only touched parts of the field. Future study work could include but not be limited to the following aspects.

1. **Full analysis of potential applications of FACTS/ESS in Bulk Power Systems.** Being the advanced power system controller, FACTS and energy storage devices can not only improve power flow control, oscillation damping, and voltage control effectively and same time economically, but also help solve some of the problems such as uneven power flow through the system (loop flows), transient and dynamic instability, subsynchronous oscillations, and dynamic overvoltage and undervoltage. The full analysis of the potential applications of energy storage devices in the bulk power systems like the Eastern Interconnection power system can give a whole picture of the benefits from the energy storage technology applications.

2. **The control coordination of FACTS/ESS for multi-control functions.** In this research, we studied solving the EAF induced problems and LFO by using the energy storage devices individually. But we did not study how to use one ESS to coordinate the control the EAF induced problems and LFO together at the same time. The system

may need the FACTS/ESS to deal with the EAF problems and LFO simultaneously in some scenarios. To do so, a special control scheme will be needed. For example, the study focuses will lie in two aspects. One is what variables will be the input of the state-space controller, and the other one is what the control objective will be.

3. **The capacity choice of the centralized ESS**. As we know, the capacity of the centralized ESS is not only related to the control effects, but also associated with the investment. The ratio of control effects and the equipment price is an important consideration for any utility. The optimization of the capacity choice of the ESS will be an important practical issue to be added.

4. **The location choice of the centralized ESS.** As the simulation results indicated in this dissertation, the locations of the centralized ESS compensators play an important role in the control effect. If the centralized compensation is preferred, the choice of the location of these compensators needs to be studied.

5. **The application of Distributed ESS.** The Distributed Energy Storage System (D-ESS) is an innovative new application of energy storage technology. As it is shown in our study, distributed energy storage devices can play a unique role in damping the inter-area mode low frequency oscillation within a wide area. Some of the benefits of using the distributed energy storage device are:
    a. Faster voltage recovery when compared centralized approach in general.
    b. Distributed sources.
    c. Modular design to meet future load growth and portable in case it has to be moved to other locations.

6. **The economic analysis of different kinds of ESS solutions.** From a customer's point of view, one of the most important considerations is the capital cost of the compensating system and its operating cost. In some applications, the dimensions and weight are also of concern. The price of the compensating system is primarily influenced by the voltage level, power level, technology used and compensator

topology. The operating cost of the compensating system is primarily influenced by the operating range of the compensating system. The economic analysis of different energy storage systems could be a future research task.

7. **Advanced control schemes.** The control schemes are critical for the full utilization of the energy storage devices. The good control scheme can make the energy storage devices more flexible and efficient to use. The utilization ratio of the whole system investment can be improved to a higher level by the advanced control technology.

8. **Wide area measurement and control.** In this study, the remote control can be implemented by the application of wide area measurement from PMUs and FNET as input. Because some power system problems like the inter-area mode low frequency oscillations span a wide area, the wide area measurement and control system will be a direct approach to solve such kinds of problem. The controller design will be a lot of easier because of the large amount of available information as feedback. More important is, wide area measurement technology will be the base in this study for both the centralized control and distributed control schemes. Optimization will be an objective of this kind of study.

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[2] Shu-Jen Steven Tsai, Li Zhang, Arun G. Phadke, Yilu Liu, Michael R. Ingram, Sandra C. Bell, Ian S. Grant, Dale T. Bradshaw, David Lubkeman, Le Tang, "Study of Global Power Frequency Dynamic Behavior of Large Power Systems", Power System Conference & Exposition, October 2004, New York, USA.

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Vita

Li Zhang

Li Zhang was born in Harbin, Heilongjiang Province in Northeast of China. He received his B.S. degree from Northeast University in Automation Engineering in 1989, his M.S. degree from Harbin Polytechnic University in Electrical Engineering in 1992, and his Ph.D. degree from Tsinghua University in Electrical Engineering in 1997. In 1997, he joined Beijing Power Supply Company in Beijing, China, as an engineer, where he was in charge of different technical management work in several key departments of this company including: Transformation Department, Transmission Department, Dispatching Center, and Foreign Affairs Departmet, conducting research projects regarding substation automation and power supply company management information system design.

From May 2001 to October 2001, he joined the Building Service Engineering Department of the Hong Kong Polytechnic University as a research fellow, conducting the study in the field of power electronics applications in power quality control in buildings, especially in the large commercial, television, and governmental buildings. From October 2001, he joined the Electrical and Computer Engineering department of Virginia Polytechnic Institute and State University as a research scientist, at the same time, he was pursuing his second degree in the filed of advanced technology applications in power system. He has been in charge of writing important proposals, conducting research projects and teaching graduate courses as a guest lecturer. He is the main contributor for several National Science Foundation funded proposals and projects.

From May 2005, he joined KEMA T&D Consulting Company as a co-op, working as a consulting engineer in assisting utilities in the U.S. and other countries all over the world, in the field of power system planning, power quality control, power electronics equipments design and application study. He is the main contributor for more than 15 key projects in KEMA T&D Consulting. He will join the Advanced Transmission Studies and Technologies Group in American Electric Power (AEP) in Gahanna, Ohio from August 2006, conducting the studies in a wide range of fields including transmission technology (R&D program), system stability, voltage coordination & reactive supply planning, three phase unbalance study, insulation coordination, transient overvoltage, generation equipment testing and analysis, EMF and induced voltage/current calculations, system restoration/emergency planning, application of phasor technology, power quality, and applications of advanced transmission technologies.

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EXPERIENCE

- **Principal Engineer**, KEMA T&D Consulting, May 2005 – May 2006
- **Research Scientist**, ECE Department, Virginia Tech, 2001 - 2004
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- **Engineer**, Beijing Power Supply Company, 1997 - 2001
- **Research Assistant**, EE Department, Tsinghua University, 1992 - 1997
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EXPERTISE

- Power System Planning, Analysis and Design
- Power Quality Study
- Power Electronics Design and Applications
- Information System Applications in Power Industry
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PSS/E, PSAPAC (IPFLOW and ETMSP), EMTP (ATP), EMTDC/PSCAD, Power Factory, NETOMAC, ASPEN, Saber, PSPICE, MATLAB, Visual Basic, Visual C, Fortran, Visual Foxpro, FrontPage, Access, Management Information System (MIS) development.