Innovative Strategies for the Hierarchical Control of FACTS

Control Logic for Flexible AC Transmission Systems

1000785

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EPRI Project Manager

A. Edris

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

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ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Gerald Thomas Heydt

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This report was prepared by

Gerald Thomas Heydt
9637 North 117 Street
Scottsdale, AZ 85259

Principal Investigator
G. Heydt

2nd Research Contractor Company Name
Chen Ching Liu
3813 82nd Avenue SE
Mercer Island, WA 98040

Principal Investigator
C. Liu

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REPORT SUMMARY

The purpose of this project is to develop a control logic concept to enhance the functionality of FACTS controllers in transmission systems. We are describing an innovative concept that can be implemented, at a future phase, in an Energy Management System with the objectives of increasing power transfer capability, stability, and reliability through hierarchical control. The scope of the work is: to identify four key strategies for FACTS controls; to prepare a technical basis for each of the strategies; to expound the capabilities of the strategies, and to compare them to each other for practical implementation; to illustrate the strengths and weaknesses of the four strategies through demonstration software codes. FACTS controllers offer the potential of improvement of ATC as well as flexible steady state power flow control and dynamic system response improvement. At this time, FACTS devices are individually controlled. The research issues include: control logic that allows maximal ATC while maintaining the system dynamic security, systematic control methodology integrating FACTS controllers and other conventional controls. The system control strategy is particularly challenging when the system dynamic security is taken into account. The new control strategies include computational algorithms and intelligent system techniques that allow the FACTS controllers to increase transfer capabilities and relieve congestive network conditions. In this report, several strategies are proposed for FACTS control logic:

- Dynamic security based FACTS control
- Intelligent system applications
- Transportation model strategies
- Fast system study methods.

The methods are described and examples are given for the implementation of these concepts. The main conclusions of this study are:

- FACTS controllers are useful for both steady state and dynamic controls in power systems. Also, the control speed capability of FACTS controllers exceeds the requirements of dynamic and steady state power system controls.
- FACTS controllers offer the possibility of transmission congestion alleviation and ATC improvement.
- FACTS controllers may be used to improve system dynamic response .
- The transportation method offers a useful method to effectuate FACTS control objectives.
- System sensory measurements should be used to improve the accuracy of the calculation of FACTS control signals.
- Intelligent methods and genetic algorithms may be used to determine the secure operating states of a power system, and these may be used to determine the ATC constrained to secure operating conditions.
- FACTS controllers offer an alternative to special protection schemes. This alternative has the advantage of not requiring generation to be taken off line.

EXECUTIVE SUMMARY

The purpose of this project is to develop a control logic concept to enhance the functionality of FACTS controllers in transmission systems. We are describing an innovative concept that can be implemented, at a future phase, in an Energy Management System with the objectives of increasing power transfer capability, stability, and reliability through hierarchical control. The scope of the work is: to identify four key strategies for FACTS controls; to prepare a technical basis for each of the strategies; to expound the capabilities of the strategies, and to compare them to each other for practical implementation; to illustrate the strengths and weaknesses of the four strategies through demonstration software codes. In a competitive environment, more FACTS are expected in the power systems. At this time, FACTS devices are individually controlled. To achieve a higher ATC for a transmission system, however, it would be desirable to look at the *FACTS control from a systems point of view*. In other words, new system control logic that allows the control of FACTS to provide maximal ATCs while maintaining the system dynamic security, including voltage security, will help transmission systems accommodate the fast increasing number of electricity transactions. The research issues include: control logic that allows maximal ATC while maintaining the system dynamic security, systematic control methodology integrating FACTS controllers and other conventional controls. The system control strategy is particularly challenging when the system dynamic security is taken into account. The new control strategies include computational algorithms and intelligent system techniques that allow the FACTS controllers to increase transfer capabilities and relieve congestive network conditions.

The main functions of FACTS controls are: power flow control; power management; voltage control; reactive power flow control; and dynamic response stabilization (i.e., damping enhancement). The response times for these control classes is generally in the 3 to 10 ms range which is readily accomplished using FACTS controllers. Proposed general control structures include hierarchical controls and transportation methods. In the case of hierarchical controls, several levels are established that progressively reach farther into the interconnected system and impact larger regions. The higher hierarchies impact the widest areas and have control objectives that relate to interconnected systems (e.g., inter-area oscillation damping; inter-area power exchange; transmission grid congestion reduction). The lower level hierarchies focus on local controls, power flow control, and system response damping.

The main conclusions of this study are:

- FACTS controllers are useful for both steady state and dynamic controls in power systems. Also, the control speed capability of FACTS controllers exceeds the requirements of dynamic and steady state power system controls.

- FACTS controllers offer the possibility of transmission congestion alleviation and ATC improvement.
- FACTS controllers may be used to improve system dynamic response .
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- System sensory measurements should be used to improve the accuracy of the calculation of FACTS control signals.
- Intelligent methods and genetic algorithms may be used to determine the secure operating states of a power system, and these may be used to determine the ATC constrained to secure operating conditions.
- FACTS controllers offer an alternative to special protection schemes. This alternative has the advantage of not requiring generation to be taken off line.

Recommendations for additional research and development include:

- The conversion of the transportation method to a simulation tested control logic for FACTS controllers.
- The incorporation of FACTS controls into optimal power flow analysis methods.
- The construction and testing of practical FACTS control software for application to an existing system.

Key specific recommendations for further work include the following:

- *Identification of the types of FACTS devices to be incorporated and develop the software models*

The types and analytical models of FACTS devices to be incorporated in the practical software should be determined in consultation with engineers from host EPRI member companies.

- *Development of practical algorithms for optimal dispatch of the Available Transfer Capabilities in interconnected power systems and remedial control*

It has been shown that FACTS controls can expand the Total Transfer Capabilities and reduce the Transmission Reliability Margin. The control logic is based on optimization methods and transportation congestion management techniques. Remedial controls using FACTS devices have also been demonstrated. Actual power system models should be developed for use with practical control logic algorithms. This involves detailed modeling of the power system and the set of identified FACTS controllers to be used. The optimization algorithms need to be tested. The concept of Pareto-optimal solutions is important here. Given that there are multiple paths for which the ATC will be dispatched, it is necessary to determine the Pareto-optimal solutions and perform tradeoff among these solutions. Considerations for the tradeoff include systems security and economics. Genetic algorithms can serve as a search engine for the Pareto-optimal solutions and a full investigation of this tool is recommended.

System dynamics need to be considered in the ATC calculation. The dynamic security criteria used by the host EPRI member company needs to be identified and reduced to a mathematical specification. The dynamic security criteria should be integrated into the ATC calculation algorithms.

In the pilot phase of this work, a relationship was identified between FACTS controllers and Special Protection Systems as *remedial controls*. If the FACTS controllers can be used effectively as remedial controls, they will be attractive tools to help avoid overloading and the associated problems that may arise. It is recommended to develop optimization algorithms that calculate the FACTS control configuration and settings for the purpose of remedial control. It will be desirable if the same computational techniques that allow the calculation of the optimal ATC dispatch will also be used for optimization of remedial controls.

- *Software implementation of the optimal ATC dispatch algorithms*

The coding of the control algorithms as efficient software is recommended. The software tools should be selected in consultation with EPRI and the host member companies. The goal is to select tools so that the developed package will be more efficient, generic and portable.

- *Validation and verification of the ATC dispatch software*

The control algorithms should be validated based on the specifications and test cases. Comments from EPRI and host companies should be requested and used for enhancement of the software. Test cases that are generic and representative should be selected so that the robustness of the algorithm can be achieved.

- *Development of implementation plans for the ATC dispatch algorithms in a practical environment*

The proposed Pareto-optimal ATC dispatch algorithm is a new tool for the power market environment. The implementation of the tool requires a thorough analysis. Considerations include the software and hardware environment, data requirements, data acquisition associated with the new tool, and market data for economic evaluation. Researchers should work with the host companies to develop implementation plans for the new ATC dispatch software.

ABSTRACT

The purpose of this project is to develop a control logic concept to enhance the functionality of FACTS controllers in transmission systems. We are describing an innovative concept that can be implemented, at a future phase, in an Energy Management System with the objectives of increasing power transfer capability, stability, and reliability through hierarchical control. The scope of the work is: to identify four key strategies for FACTS controls; to prepare a technical basis for each of the strategies; to expound the capabilities of the strategies, and to compare them to each other for practical implementation; to illustrate the strengths and weaknesses of the four strategies through demonstration software codes.

The EPRI Electricity Technology Roadmap provides a clear vision for the future of FACTS application. 'As FACTS devices are extensively deployed throughout the North American grid, system operators will be able to dispatch transmission capacity within the primary interconnection regions, thus facilitating open access.' The most important limitation for the Available Transfer Capability (ATC) in the open access transmission environment today is probably *voltage security*. At this time, FACTS devices are individually controlled. To achieve a higher ATC for a transmission system, however, it would be desirable to look at the *FACTS control from a systems point of view*. In other words, new system control logic that allows the control of FACTS to provide maximal ATCs while maintaining the system dynamic security, including voltage security, will help transmission systems accommodate the fast increasing number of electricity transactions. The research issues include: control logic that allows maximal ATC while maintaining the system dynamic security, systematic control methodology integrating FACTS controllers and other conventional controls. The system control strategy is particularly challenging when the system dynamic security is taken into account. The new control strategies include computational algorithms and intelligent system techniques that allow the FACTS controllers to increase transfer capabilities and relieve congestive network conditions.

In this report, several strategies are proposed for FACTS control logic:

- Dynamic security based FACTS control
- Intelligent system applications
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- Fast system study methods.

Among the techniques studied for FACTS controls are intelligent systems. Intelligent system techniques include expert systems (or knowledge-based systems), artificial neural networks, fuzzy logic and evolutionary algorithms. All of them find useful applications associated

with FACTS. These applications are different based on the diverse natures and capabilities of intelligent system techniques. This chapter discusses each of the techniques and its potential applications related to FACTS devices. The results of this chapter can be summarized by:

- Knowledge-based systems can serve as tools to assist system operators in identifying scenarios in which operator-initiated FACTS control is beneficial.
- Artificial neural networks can be used to calculate the appropriate control settings for FACTS devices.
- For FACTS control, fuzzy logic can be used to describe uncertain system parameters or constraints for the optimal power flow solutions. This is particularly useful for the calculation of transmission reliability margins associated with the ATC.
- Genetic algorithm techniques are proposed for heuristics-based search of locations and settings of FACTS devices that result in high ATC values between areas in an interconnected system.

Transportation methods are also studied as the basis of FACTS controls. Transportation methods are based on the conservation of power. These expressions alone do not give sufficient equations for the development of FACTS device control signals, but in combination with bus load measurements, and line power flow measurements, sufficient degrees of freedom are available for an accurate control strategy solution. The method is easily programmed in higher level programming languages, it has been shown to be valid for small examples, and it has an adaptive nature which should allow for the accurate calculation of a control signal. The main limitation of the method is in accuracy of the calculation of the control signal; this can be controlled by augmenting the method with measurements and careful design of the placement of the measurements. The main advantage of the method is in calculation speed and the fact that relatively little memory is needed for the calculation. The method is best suited for a sinusoidal steady state solution of the FACTS control problem, although transient stability enhancement is also possible.

The main conclusions of this study are:

- FACTS controllers are useful for both steady state and dynamic controls in power systems. Also, the control speed capability of FACTS controllers exceeds the requirements of dynamic and steady state power system controls.
- FACTS controllers offer the possibility of transmission congestion alleviation and ATC improvement.
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- The construction and testing of practical FACTS control software for application to an existing system.

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NOMENCLATURE

A	A general rectangular matrix
A, B, C	Energy market agents
A, B, C, E, F, G, H	Subvectors of line flows and bus injected powers
ACE	Area control error
AEP	American Electric Power Company
AGC	Automatic generation control
ATC	Available transfer capability
b	Vector
BPA	Bonneville Power Administration
$c(t)$	Coefficient in transmission formula
CBM	Capacity benefit margin
CPU	Central processing unit
CSC	Convertible static compensator
D_b	Desired value of vector b
D_E	Desired value of vector E
EPRI	Electric Power Research Institute
ETMSP	Extended Transient and Midterm Stability Program
E, F	Right and left singular vectors of a rectangular matrix A
f	System dynamic equations, state equations
FACTS	Flexible AC transmission systems
FCITC	First Contingency Incremental Transfer Capability
FCTTC	First Contingency Total Transfer Capability
FERC	Federal Energy Regulatory Commission
F_{node}, F_{branch}	Generalized flows at a node or in a branch
$g(x, z_T, u)$	Constraint equations
GaN	Gallium Nitride
GTO	Gate turn-off thyristor
$H(x)$	Line flow and bus voltage limits
I	Current, identity matrix
IGBT	Insulated gate bipolar transistor
IPFC	Interline power flow controller
ISO	Independent system operator
j	$\sqrt{-1}$

J	Residual (error) in state estimation
J	Jacobian matrix
$J1.\ J2, \ldots, J_{\mapsto}, J_{\updownarrow},$	Submatrix partitions of the Jacobian matrix
k	Equivalent susceptance
k	Number of transactions in deregulated system environment
$k(J)$	Spectral radius of matrix J
L	Incidence matrix
LEOS	Low Earth orbit satellite
M	A binary integer used in connection with a genetic algorithm
M_A, M_B, M_G	Measurements of vectors A, B, G
N	Arbitrary integer, number of equations in a state estimator
$N\text{-}1$	Reference to a single line outage contingency
$N_A, N_B, N_C, \ldots$	The number of rows in vectors $A, B, C, \ldots$
NATC	Non-recallable ATC
NERC	North American Electric Reliability Council
NRES	Non-recallable reserved amount.
NYPA	New York Power Authority
OASIS	Open Access Sametime Information System
OPF	Optimal power flow
P	A binary integer used in connection with a genetic algorithm
P, p_I	Active power
P_c, P_{ctrl}	Controlled power
PQ, PV	Type of system bus used in power flow study in which P, Q or $P, \|V\|$ are specified
PSS	Power system stabilizer
PWM	Pulse width modulation
Q	Reactive power
R	Resistance
RATC	Recallable transmission service
rms	Root mean square
RSP	Related system path method for determining ATC
S	Complex power
S_{bus}	Injected bus complex power
SCADA	Supervisory control and data acquisition system
SCR	Silicon controlled rectifier
SiC	Silicon Carbide
S_{line}	Line flow complex power
SPS	Special protection scheme
SSSC	Static synchronous series compensator
STATCOM	Static synchronous compensator
SVC	Static var compensator

T, t	A time window, time
TCSC	Thyristor controlled series capacitor
TRM	Transmission reliability margin
TTC	Total transfer capability
TVA	Tennessee Valley Authority
u(t)	FACTS control signal
UPFC	Unified power flow controller
V	Bus voltage
$\|V_c\|, \|V_u\|$	Controlled and uncontrolled bus voltage magnitudes
W	Weighting matrix
WAPA	Western Area Power Administration
X	Reactance
X	State vector
x, x(t)	A system state
X_C, x_L	Capacitive and inductive reactance
z_T	System variables such as bus injections and line constants
□	Bus voltage phase angle
ƛ*P*, ƛ*Q*	Mismatch active and reactive power
λ	Eigenvalue
ħ	Vector of state variables to be estimated
Σ	Diagonal matrix of singular values of a rectangular matrix *A*
□	Frequency in r/s
$(*)^+$	Pseudoinverse of a matrix
$(*)^T$	Transpose of a matrix or vector
$\overline{(*)}$	Estimate of a quantity
$(*)^*$	Optimal value of a quantity

CHAPTER 1

CONTROL LOGIC FOR FACTS

1.1 Scope

The purpose of this project is to develop a control logic concept to enhance the functionality of FACTS controllers in transmission systems. We are describing an innovative concept that can be implemented, at a future phase, in an Energy Management System with the objectives of increasing power transfer capability, stability, and reliability through hierarchical control. The scope of the work is:

1. To identify four key strategies for FACTS controls
2. To prepare a technical basis for each of the strategies
3. To expound the capabilities of the strategies, and to compare them to each other for practical implementation
4. To illustrate the strengths and weaknesses of the four strategies through demonstration software codes
5. To document the research.

1.2 Project Management and Report Preparation

Dr. Adel-Aty Edris served as the project manager at EPRI. The investigators are Dr. G. T. Heydt and Dr. Chen Ching Liu. Dr. Heydt is with Arizona State University, and Dr. Liu is with the University of Washington. This report was prepared as a cooperative effort between the authors, but the main responsibilities for Chapters 3 and 4 were Dr. Liu and for Chapters 5 and 6 assigned to Dr. Heydt.

1.3 Introduction and Motivation

Traditionally, power system controls are limited mainly to generator controls and line switching. In recent years, the use of solid state switching technology has been proposed for more effective power flow control. The potential of solid state 'flexible AC transmission system' (FACTS) devices is exactly that: the use of various electronic switching technologies for high power (e.g., multi-megawatt) flow control. As the solid state technologies progress and make this potential a reality, it is important to develop, in parallel, system control strategies for FACTS controllers.

The EPRI Electricity Technology Roadmap provides a clear vision for the future of FACTS application. ‘As FACTS devices are extensively deployed throughout the North American grid [J14], system operators will be able to dispatch transmission capacity within the primary interconnection regions, thus facilitating open access.’ The most important limitation for the Available Transfer Capability in the open access transmission environment today is probably *voltage security*. Well known FACTS applications include advanced series capacitor at WAPA, BPA’s thyristor-controlled series capacitor, TVA’s static synchronous compensator, the convertible static compensator (CSC) at NYPA, and AEP’s unified power flow controller. These control *concepts* are primarily based on steady state control concepts, i.e., control of voltages, MVARS, and power flows. In a competitive environment, more FACTS are expected in the power systems. At this time, the FACTS devices are individually controlled. To achieve a higher ATC for a transmission system, however, it would be desirable to look at the *FACTS control from a systems point of view*. In other words, new system control logic that allows the control of FACTS to provide maximal ATCs while maintaining the system dynamic security, including voltage security, will help transmission systems accommodate the fast increasing number of electricity transactions. The research issues include: control logic that allows maximal ATC while maintaining the system dynamic security, systematic control methodology integrating FACTS controllers and other conventional controls. The system control strategy is particularly challenging when the system dynamic security is taken into account. For example, if voltage security is the limiting factor of the ATC, how does FACTS control increase the voltage stability margins and the ATCs as the system operating conditions change with the electricity market? The new control strategies include computational algorithms and intelligent system techniques that allow the FACTS controllers to increase transfer capabilities and relieve congestive network conditions.

In transportation, highway network congestion can be managed by traffic flow control. For example, metering and flash lights at highway entrances help to manage the traffic flow. In the power system environment, the congestion management may be viewed as a power flow control problem. FACTS controllers provide powerful control devices that provide dynamic voltage control and regulation of the flows on transmission lines. Analytical methods can be formulated for the power flow control problem. Clearly a power system is not a transportation network as a power system is subject to different physical laws. The system wide power flow control problem considering various ATCs and dynamic security is a new challenge to power system engineers.

FACTS controllers are fast. To take advantage of these fast controllers, the new system control logic also has to be fast. Modern computer and communications technologies have provided a powerful environment for wide area control. To calculate the appropriate controls for an operating condition, the new system control logic must be able to analyze the ATC and system security quickly and identify the most beneficial control devices.

Based on the above discussion, this proposal deals with the exposition of four main strategies for FACTS device controls. The strategies are broadly classified as:

- Dynamic security based FACTS control
- Intelligent system applications
- Transportation model strategies
- Fast system study methods

1.4 Coverage of this Report

The project is organized into six tasks:

Task 1 - Dynamic security based FACTS control
Task 2 - Intelligent system applications
Task 3 - Transportation model strategies
Task 4 - Fast system study methods
Task 5 - Coordination of results.

This report is the result of Task 6 of the cited research project. Also, an IEEE technical paper was prepared on the main points [J16]. The statements of work for each task are shown in Table 1-1.

1.5 FACTS Control Logic Literature

It is reasonable to state that the literature of flexible AC transmission systems, the concept, controls, devices, and auxiliary considerations, is huge. With regard to FACTS controls themselves, the literature can be organized into several main segments: transient controls vs. sinusoidal steady state; operating considerations vs. planning; literature that focuses on the devices themselves versus their placement and analysis. Table 1-2 shows an organization of the literature. This table is a guide to the selected, recent literature citations that appear at the end of the report. General references cited in the report text appear in section [J] of the reference list.

It is worthwhile to provide a brief sampling of the literature and the reported analysis and research in the area of FACTS controls:

Table 1-1
Statement of work for each project task

Task	*Description*	*Statement of Work*
1	Method #1 Dynamic security based FACTS control	Analyze FACTS control from a *systems* point of view. Define new system control logic that allows the control of FACTS to provide maximal ATCs while maintaining the system dynamic security, including voltage security, Discuss how transmission systems can accommodate the fast increasing number of electricity transactions. Define a systematic control methodology integrating FACTS controllers and other conventional controls. Discuss feasibility of the defined concepts. Illustrate the strengths and weaknesses of the strategy through demonstration software.
2	Method #2 Intelligent system applications	Define new control strategies including computational algorithms and intelligent system techniques that allow FACTS controllers to increase transfer capabilities and relieve congestive network conditions. Analyze how system operators can dispatch the transmission capabilities to facilitate open access. Intelligent system techniques include knowledge-based systems, neural networks, fuzzy logic and heuristic (or evolutionary) algorithms. Illustrate the strengths and weaknesses of the strategy through demonstration software.
3	Method #3 Transportation model strategies	Perform a literature search on the subject of transportation systems analysis in power flow applications; and research the application, its strengths and weaknesses, for application of a high speed, on-line sinusoidal steady state analysis of large, interconnected power systems. Also, perform example studies to demonstrate the concept. Illustrate the strengths and weaknesses of the strategy through demonstration software.
4	Method #4 Fast system study methods	The subject of fast sinusoidal steady state analysis of power flow for large interconnected systems shall be researched and summarized in a preliminary written report. The strengths and weaknesses of the methods used shall be documented. Analysis of error of these techniques shall be performed. Illustrate the strengths and weaknesses of the strategy through demonstration software.
5	Coordination of results	Assemble the results of Tasks 1 – 4, and compare the results critically for applications of FACTS controllers. The controller design will be based on sinusoidal steady state analysis, but applications in transient response enhancement will be included. The comparison of techniques will be prepared in an intermediate report.
6	Documentation	Results of tasks 1-4 of the project shall be fully documented in the form of a final report. The intermediate report generated in Task 5 shall be reviewed and modified as needed, and this shall be integrated into the final report. The final report shall be presented to EPRI for its assessment and comments, and corrections and additions shall be made as needed.

Table 1-2
Organization of FACTS literature
(citations refer to references cited at the end of this report)

	Modeling and analysis	*OPF and dispatch*	*Stability*	*Specialized control structures*	*Device applications and placement*
Sinusoidal steady state	[A1]-[A28]	[B1]-[B14]		[C1]-[C23]	[D1]-[D35]
Transient	[E1] – [E6]		[F1]-[F15]	[G1]-[G16]	[H1] – [H21]
*"Coordinated"**	[I1]-[I7]				

*The term *coordinated* refers to controls that consider both transient and sinusoidal steady state modes of operation.

FACTS controls for optimal power flow

FACTS controls for optimal power flow have been proposed [B1] – [B12]. The basic method of analysis and implementation is the sinusoidal steady state modeling of FACTS controllers, generally as voltage and current sources, with losses and phase shifts modeled as discrete devices. The concept is to replace conventional P-V and PQ buses in power flow studies by new bus types in which the FACTS controls are implemented. The concept of OPF has been implemented and tested with synthetic data. The placement of FACTS controllers to create the best effect has been addressed but not fully solved. The general methods have been demonstrated to work for the control of flows between areas and companies: the concept is clearly aimed at the deregulated power market. The issues of conflicting controls (i.e., entity A requests a certain dispatch, entity B requests a different dispatch) have not been clearly addressed. The state of the art is that using fairly simple models and conventional OPF concepts, satisfactory sinusoidal steady state OPF solutions can be obtained including FACTS controllers.

Artificial intelligence applications in FACTS technology

There are not many references that target specific applications of artificial intelligence methods to FACTS technologies, but there are many references to applications in power engineering in general. For example, [J1] and [I7] contain an overview. Reference [C2] relates to fuzzy logic applications in FACTS applications, and [H11] deals with rule based methods for power system controls – including those with FACTS controllers. Special attention is drawn to [G14] that relates to the application of a genetic algorithm for fuzzy controls of FACTS controllers.

Stability enhancement using FACTS controllers

Because of the cost of FACTS devices, it is important to include all elements of benefit to demonstrate a favorable cost to benefit ratio. The improvement of system dynamic response is a critical element in this assessment. The improvement of dynamic response occurs because of the near instantaneous capability to control power flow in lines. The essence of the idea is the enhancement of system damping. This is engineered as the design of FACTS controls such that the controlled system has more negative real parts of system eigenvalues. The concept of system eigenvalues is inherently a linearization of the actual nonlinear system. Nonetheless, the linearization and subsequent movement of system poles, or eigenvalues, to the left of the $j\omega$ axis insures that local performance is better damped. The concept is identical to the design of power system stabilizers (PSSs). In the case of PSSs, the controlled variables are mainly the generator field currents. These controls have the limitation of field time constant (which is measured in seconds) [J3]. In the case of FACTS controllers, there is no high field inductance, and the control action can occur at the millisecond range. A realistic assessment of the speed of the control is the time required for the identification of the control action (about one or two cycles in a 60 Hz system), followed by a transmittal of the control signal (less than 2 ms if hard wire or microwave is used, less than 10 ms if low Earth orbit satellite (LEOS) transmission is used), followed by the actual control setting of the FACTS controller. The latter is in the 1 ms range. Therefore, a realistic estimate of response time for a FACTS controller is 20 – 44 ms. The literature describes various damping strategies such as the utilization of local measurements plus the calculation of an energy function [F8]; affine controls based on precalculated values [C3] – [C6]; intelligent and neural network based methods [A14], [C3]. [F4], [H8]; static linearization [A17], [E1]; hierarchical methods [F4]; and target oriented methods [C2], [G15]. In the case of the latter, a target response is precalculated, and the control required to produce that response is back-calculated. This method is also termed 'inverse control'. Various forms of eigenanalysis and eigen-sensitivity have been proposed and demonstrated: a sampling includes [E6], [J9]. Wide area measurements in connection with PSS design appear in [J4], [J6]. The concept of controllability of systems with FACTS controllers is considered in [C3]. Fuzzy logic controllers appear in [F1] – [F2], [G14].

Coordination of controls

The concept of coordination of controls refers to the design of several control systems that may have different objectives, but that nonetheless operate at the same time harmoniously; or, the design of several control objectives in a single control system. Because of the inherent flexibility of FACTS, their use is expected to be maximized. The two main types of control objectives are transient stability (including damping enhancement) and sinusoidal steady state operation. In the case of the former, the objectives generally relate to stability and damping, and these objectives operate in the short term range (e.g., less than a second does, and perhaps in the millisecond range). The sinusoidal steady state operation necessarily operates longer than one cycle (i.e., 1/60 second), and frequently falls into the range of several seconds or longer. The concept of coordinating the controls relates to:

- Identification of modes of operation using system measurements
- Switching controls as needed from the transient stability mode to the sinusoidal steady state
- Utilization of both higher and lower level signals in order to accommodate local needs as well as wide area considerations.

The concept of coordinated controls is discussed in [D9] and [G4]. A specialized coordination of controls for a static var compensator is shown in [H6]. References [I1] – [I7] deal with coordinated controls for FACTS controllers.

Additional remarks

As an indicator of the current interest in FACTS controls, note that at the IEEE 2000 Summer Power Meeting Seattle, there were at least 28 technical papers that dealt with FACTS technology as the main subject [A27, A28, B13, B14, C20-23, D29-33, E6, F11-15, G14-16, H21, I6, I7, J9-11]. A preliminary report summarizing the subject of control logic for FACTS controllers was prepared for the 2001 IEEE Summer Meeting [J16].

CHAPTER 2

REQUIREMENTS FOR FACTS CONTROLLERS

2.1 General Requirements

The main requirements for FACTS controllers can be categorized as sinusoidal steady state or transient. The sinusoidal steady state controls are basically power flow controls. These controls are intended to perform economic dispatch and transaction sales functions. The transient controls are intended to stabilize the system by adding damping. Although the steady state and transient functions are distinct, there is a proposed plan to coordinate the two functions (i.e., a 'coordinated' control). The motivation for coordinating controls is to balance the tradeoff between the two objectives, and to rapidly transition between the objectives as needed.

The basic needs of several types of FACTS controllers are listed in Table 2-1.

The temporal needs of FACTS controllers (i.e., the response time) depend on the mode of operation. Power flow control applications are slower than transient applications. The power flow controls generally rely on the average power and control of average power. In the steady state mode, that is for power flow control, the basic response time is a few cycles (of the 60 Hz wave). On the basis of the utilization of average power (i.e., 'active power'), a realistic lower limit of power flow control response time is about 17 ms. VAr flow control and var injection also falls into the same response time range. In some applications, many cycles will elapse in the process of control, and response time of 100 ms or more might be tolerated. The dynamic mode of operation, namely damping enhancement, requires a much shorter response time. The full utilization of FACTS controllers for transient response enhancement entails damping improvement, and coordination with power system stabilizers (PSSs). This is in the range of ¼ of a cycle or about 3 ms at the lower limit. Table 2-2 shows estimates of response time requirements for FACTS devices and their controllers.

Table 2-1
Requirements for FACTS controllers

<table>
<tr><th>Type of control</th><th>Steady state requirement</th><th>Dynamic requirement</th></tr>
<tr><td>Power flow control</td><td>• Control of thyristor delay angle based on power flow set point (from SCADA)
• Fixed active power flow control strategy to control thyristor delay angle
• The magnitude and phase of an injected voltage in series with the controlled transmission line must be controlled</td><td rowspan="4">• Few transient strategies have been put forward for control of devices such as unified power flow controllers. The basic requirement is the control of a PWM inverter to insert a correction signal in a series arrangement with a line. The controller must generate a suitable PWM amplitude modulation index in real time.</td></tr>
<tr><td>Power management</td><td>• An interline power flow controller (IPFC) is used to inject power from an adjacent circuit into a controlled line</td></tr>
<tr><td>Voltage control</td><td>• Fixed voltage feedback controller
• Supervisory command control to set voltage</td></tr>
<tr><td>Var control</td><td>• In static var compensators and thyristor controlled capacitors, reactive power control may be present. Often this is a supervisory action, but an on-line voltage control may be implemented to effectively control vars.
• In a STATCOM, current is controlled and injected into the controlled bus.
• For unified power flow controllers, fixed bus voltage strategies may be effectively var controls. The controller injects a controlled reactive current (capacitive or inductive).</td></tr>
<tr><td>Dynamic response stabilization</td><td>• Steady state stability
• N-1 contingency analysis and passing ‘tests’ for contingency cases</td><td>• The main concept is to add damping to the system, and to supplement power system stabilizers.</td></tr>
</table>

Table 2-2
Approximate response time requirements for FACTS controllers for various control regimes

Type of control	Estimated response time requirement	
	Steady state requirement	*Transient requirement*
Power flow control	Several cycles (e.g., 150 – 300 ms)	Rapid, on-line tracking capability. Estimates are in the quarter cycle range (e.g., 3 - 10 ms)
Voltage control	Several cycles, but faster response time as compared to power flow control to track load variation (e.g., 50 - 200 ms)	Quarter cycle requirement as evidenced by transient voltage restorer applications (e.g., 3 - 10 ms)
Var control	50 - 200 ms	Vars are generally defined for sinusoidal steady state for $T > 1/60$ second
Stability enhancement / coordination with PSSs		About 3 ms

The dynamic range of FACTS controllers is generally expressed in per unit on the basis of the circuit rating. For unified power flow controllers, the range is generally accepted to be either zero to one per unit, or !1.0 depending on the design, protection and auxiliary equipment on the line. The bandwidth of FACTS controllers can be estimated by evaluating the inverse of the reaction time requirement. For power flow applications, this is in the range 0 – 3 Hz, and for transient applications, 0 – 350 Hz.

2.2 Dispatch of Transmission Capabilities Using FACTS

The U.S. power industry is going through an unprecedented restructuring over the last several years. The Federal Energy Regulatory Commission (FERC) Order 888 and Order 889 in 1996 provide the regulatory framework for open access to the transmission grid. In this new open access environment, generation companies can access the transmission grid to deliver electricity to the consumers. Today, Independent System Operators (ISOs) or their equivalents are responsible for monitoring and operation of the transmission grids. ISOs may not be the owners of the grid, however. Participants of an electricity market can acquire information concerning transmission capabilities from the Open Access Sametime Information System (OASIS).

The North American Electric Reliability Council (NERC) has developed definitions and guidelines for the Available Transfer Capabilities (ATC). Generally speaking, the ATC of a transmission system is its Total Transfer Capability (TTC) minus the committed (scheduled) amount, the transmission reliability margin (TRM) and the capacity benefit margin (CBM). Here TRM is the amount of transmission capacity reserved to ensure that the system is secure under contingency conditions and CBM is the transmission capability that allows a system to import electricity to meet the reliability requirements. It is important to note that ATC is defined from an area to another, say, from area A to area B. This *fictitious* path from A to B does not necessarily correspond to a physical transmission line in the power grid. Transmission is an important issue for an electricity market. Congestion of the transmission grid may affect the transmission pricing, leading to higher risks for the market participants. Congestion management is the responsibility of the ISOs.

There is a potential for gaming in the transmission system in a competitive market. For example, suppose there are three players in an electricity market, A, B and C. It is assumed that A has the lowest generation cost and has the capacity to serve the total load in the system. In other words, A would capture the entire market share if the market were determined solely by the production cost. The market, however, relies on the transmission system to deliver the electric energy. Suppose B and C belong to the same company and B shares the transmission capacity of a line with A. A and B may be electrically close to this line and they depend on this line to deliver the electricity. Now the market determines the amount of electricity to buy or sell based on bids from the three participants. Note that B and C have higher generation costs relative to A. In a gaming scenario, B can bid lower than A's cost of generation so that B will be selected by the market to supply MW. Since B and A share transmission access to the market and B is taking the transmission capacity so that the market is no longer able to buy from A, the market will have to turn to C to purchase MW in order to meet the load demand. At this time, C is a monopoly and therefore it is possible for C to bid high so that it is able to gain profit and compensate for B's losses. The result of gaming by B and C leads to the loss of A's market share. The above scenario is likely to occur in some market structures such as the U.K. market. It is important to design the market structure to avoid such gaming that can unfairly increase the overall costs to the consumers. An analysis of gaming in an electricity market using transmission capacities is provided in [J12].

In the market environment, the number of electric energy transactions is expected to increase significantly. In this environment, it is desirable for the transmission operator to accommodate as many transactions as possible. However, the transmission system operator also has to take into account the system security and reliability requirements. Since the energy transactions are market driven, the transmission system capacity also has to be more flexible in order to provide access to the transactions. FACTS controllers provide a great opportunity to dispatch the transmission capabilities in the open access environment. Figure 2-1 is an illustration of the three layers - Transactions, Transmission and Controls. It is the goal of a transmission system operator to use FACTS and other control devices to expand the transmission capability so that the transactions can be accommodated as much as possible.

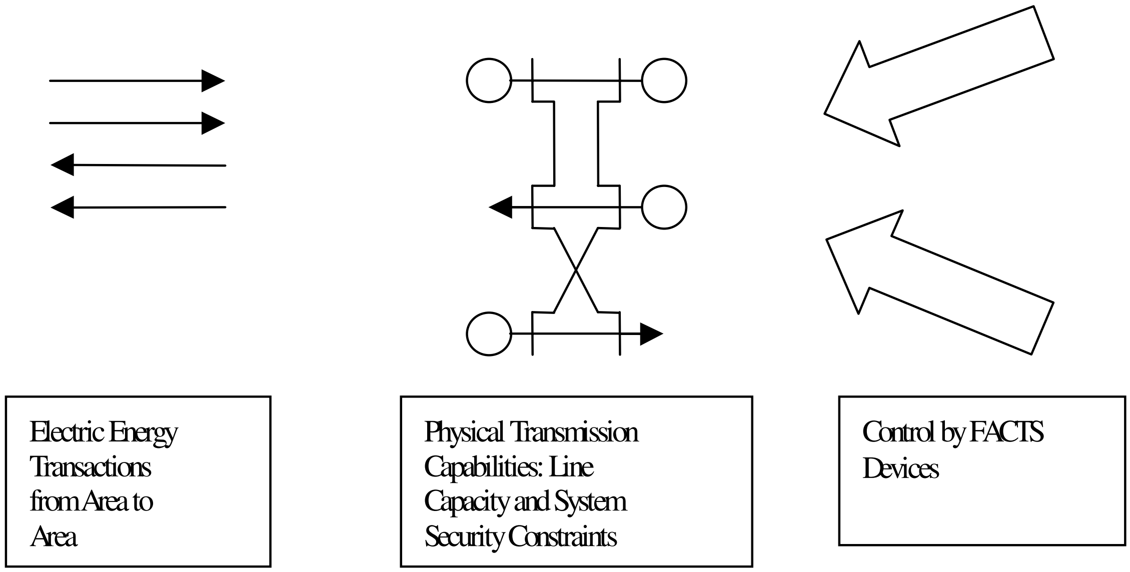


Figure 2-1
Transactions, transmission, and control layers

Based on the steady-state formulation described here, an optimization problem is formulated as,

$$\min_{u} \Sigma P_i$$

Subject to

$$f(x, z_T, u) = 0$$
$$g(x, z_T, u) = 0$$
$$h(x) \leq 0 \text{ (line flow and bus voltage limits)}$$
$$u_{min} \leq u \leq u_{max}$$

Note the example objective function here is to minimize the system losses. A more interesting objective function would be to minimize the 'unmet' demands for transmission capabilities. This new objective is expected to become desirable in the competitive environment. *FACTS controllers can be modeled as injections instead of impedance elements.* These injection values depend on the settings of the FACTS controllers. Based on this model, the steady state power flow methods can be used determine the resulting power flow patterns for the given FACTS parameter values.

If transmission is a service for profit, the objective function can be the sum of all transmission charges that the market participants have to pay. In a simple case, this can be a function of the MW amounts delivered by the grid and possibly other fixed costs. The scenario becomes more complex if concepts such as Fixed Transmission Rights have to be incorporated. It is also possible that some FACTS controls are acquired as ancillary services and therefore their costs depend on the market clearing result.

Based on the above formulation, the concept of FACTS control is identical to the traffic control through metering at the freeway entrances. The traffic metering is based on the congestive conditions on the freeways. The traffic condition is monitored through cameras installed along the freeway. Through metering, the 'injections' into the freeways are controlled in order to relieve congestion. Since FACTS controllers can also be modeled as bus injections, the FACTS settings alter the injection amounts in order to manage the power flow congestion. The difference, however, is that a power grid is an electrical network that must satisfy a different set of physical laws. Recall that ATCs are not necessarily physical paths on the power grid. Therefore congestion may take place on transmission lines that extend beyond the 'from' and 'to' areas of an ATC path. Congestion in a power grid can occur due to transmission line thermal constraints or system security constraints. Congestion management can be performed by FACTS controls. In some market models, controls such as voltage / var devices are considered ancillary services. In this case, FACTS controls are compensated by the market value. That is, a bidding process will determine which devices are needed and how the market will achieve the required controls at the minimal cost. The market structure is an important factor to create an incentive for installation of FACTS. In [J13], an optimization method is formulated that enables the ISO to make least cost decisions for purchasing ancillary services.

2.3 Types of Controls

Flexible AC transmission technologies depend on the actual type of FACTS controller used, the objectives of the controls, the detailed nature of the elements used to effectuate the control, and other design factors. There are many potential FACTS controllers but the main types can be categorized as:

- Shunt devices that inject current into the network
- Series devices that insert a series voltage into a transmission circuit
- Back-to-back converters that allow control of power flow and other electrical parameters.

Control strategies depend on the technology used as well as the detailed designs of the implementation of these FACTS controllers. Examples of these device details are discussed below, and some conclusions are made on the requirements for control logic.

Each of the three main classes listed above may be implemented in a variety of ways. As an example, solid state switches may be used in a variety of AC/DC – DC/AC back-to-back converter configurations. Each of these configurations may be implemented in an actual design using a range of semiconductor switches such as silicon controlled rectifiers (SCRs), gate turn-off thyristors (GTOs), MOSFET controlled thyristors (MCTs), insulated gate bipolar transistors (IGBTs) and many other devices. The SCR (thyristor) switches are classic devices used in many power switching applications over a very wide range. They have been used for many years in such applications as high voltage DC and controlled, forced commutated rectifiers and inverters. The SCR type controls are limited in response speed in comparison with transistors, but the great advantage of this switch is the power handling capability. Switches in the 8 kV, 1 kA range are readily available, and the cost is reasonable. The promise of exotic new semiconductors such as GaN and SiC have the promise of significantly increasing individual switch capability.

A full discussion of the capabilities of each type of semiconductor switch, application of those switches to the specific FACTS controller selected, and the ways in which the semiconductor switches are configured in order to implement the design, are beyond the scope of this report. However useful references in this area include the many power electronics textbooks that are currently available (e.g., Mohan, [J4]). Bose [J15] appears to give an annual update on semiconductor switch capabilities and a resume of recent applications. From the point of view of FACTS control logic requirements, contemporary semiconductor switches and typical configurations of controllers are easily capable of ¼ cycle (i.e., about 4 ms) switching well into the 100 MVA range. Much faster and higher power switching (and, hence, control) are within the capabilities of contemporary technologies, and there is the promise of lower cost, fast, high power semiconductor switches available commercially by 2010 [J15].

2.4 Hierarchical Control Structure Using Transportation Methods

General remarks

Hierarchical structures are common in nature and man made infrastructures. For example, the hierarchy of American government is that there is a local mayor, a state governor, a national congress, and a president. One might consider the United Nations as a super-national agency. The smaller local governments act relatively quickly, they deal with local concerns, and they have policies that impact only local population. As one moves up the hierarchy, measurements of public opinion and needs are passed vertically to higher hierarchies. The higher infrastructures act less quickly, they deal with an ever-widening population, and they have different goals from the local structures. The higher infrastructures may pass information (e.g., 'signals') horizontally to corresponding governments, and the higher structures generate controls that are passed downward to effect desired wide area objectives. This general concept is illustrated pictorially in Figure 2-2. In Figure 2-2, the upward arrow indicates that measurements are passed upward, the downward arrow indicates that controls are passed downward, and the horizontal arrow indicates the transfer of information from area to area. The upper box is the supervisory hierarchy, the middle box is the intermediate level (and may consist of many intermediate levels), and the lower box is the local control and measurement structure. Below the entire hierarchical structure is the device(s) under control in one or more regions (areas, control areas).

Application to FACTS controls

The general concept of hierarchical control may be used in any application in which there is a natural dichotomy of levels: for example, the American government illustration given above. In the case of FACTS controllers, there are two dichotomies: steady state vs. transient; and local vs. wide area. This generalized structure is depicted in Figure 2-3. Several usual and not-so-usual functions are tabulated in the partitioned region. To fully utilize the flexibility and speed of FACTS controllers, both steady state and transient functions must be implemented. These are coordinated controls. Under this assumption, the natural hierarchical structure of a FACTS controller is shown in Figure 2-4. In Figure 2-4, controls on the basis of local, control area, and wide area are depicted.

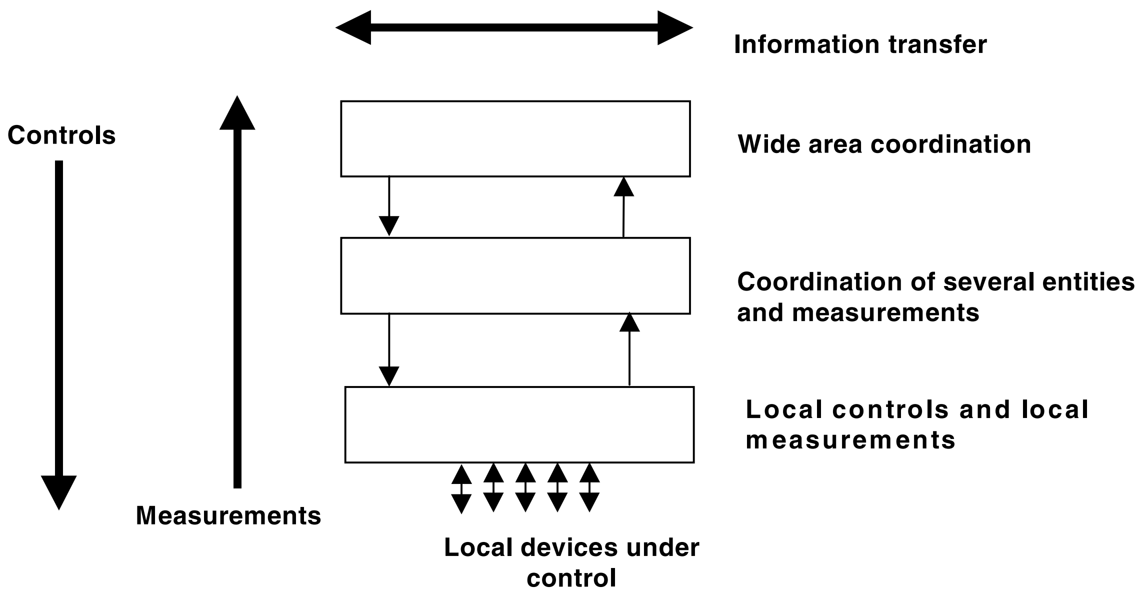


Figure 2-2
Illustration of a general hierarchical structure

	Steady State	*Transient*
Wide area	• N-1 contingency dispatch • OPF • Constrained OPF • Power flow control and management	• Wide area power system stabilizers
Local	• VAr control • Voltage regulation / setting	• Power conditioning • PSSs

Figure 2-3
Dichotomies of controls of a power system with FACTS

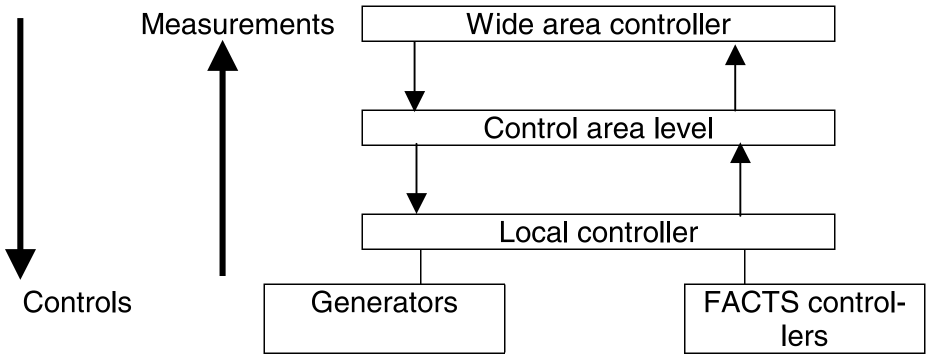


Figure 2-4
Hierarchical control of FACTS controllers

Objectives of the hierarchical levels

The control objectives of the hierarchical levels must reflect the nature of wide area control at the upper levels – with its longer term calculation requirements and wide area of impact; and the nature of the intermediate level which focuses on control area strategies, area control error, and some dynamic considerations; and finally the lowest hierarchical level which is the local level. At the local level, the controller is concerned with voltage support, var management, some power conditioning, measurement of generator output, and application of control signals to all the controls. Following the format of Figure 2-2, Table 2-3 shows the nature of the control objectives in a three tier hierarchical FACTS controller, and Table 2-4 shows the information, signal flow, and measurements in a three tier hierarchical FACTS controller.

Table 2-3
Control objectives of a three tier hierarchical FACTS controller

	Steady state	*Dynamic*
Wide area	• N-1 contingency analysis and constrained dispatch • OPF • Constrained OPF • Power flow control and management	• Wide area PSS
Control area	• Area control error management • Tie line flow control	• Added damping
Local	• Var control • Voltage regulation • Power setting (manual dispatch) • Voltage collapse detection and management	• PSS • Power conditioning

Table 2-4
Signal flows in a three tier hierarchical FACTS control

	Measurement	*Control*	*Signal exchange*
Wide area	• From control areas	• To control areas	--
Control area	• From local controllers	• To local controllers	• Between control areas
Local	• From generators, tie lines, FACTS controllers	• To PSSs • To FACTS controllers • To boiler and turbine controls • Special protection / remedial action schemes	• Between adjacent generating units

2.5 Summary

The main functions of FACTS controls are: power flow control; power management; voltage control; reactive power flow control; and dynamic response stabilization (i.e., damping enhancement). The response times for these control classes is generally in the 3 to 10 ms range which is readily accomplished using FACTS controllers. Proposed general control structures include hierarchical controls and transportation methods. In the case of hierarchical controls, several levels are established that progressively reach farther into the interconnected system and impact larger regions. The higher hierarchies impact the widest areas and have control objectives that relate to interconnected systems (e.g., inter-area oscillation damping; inter-area power exchange; transmission grid congestion reduction). The lower level hierarchies focus on local controls, power flow control, and system response damping.

CHAPTER 3

DYNAMIC SECURITY BASED FACTS CONTROL

3.1 Expanding Transmission Access Using FACTS Control of System Dynamics

In a simplified view, an electric energy transaction can be modeled as a set (*A, p, B*), where *A* is the point of delivery, *p* is the MW amount of the transaction and *B* is the point of receipt. Given a set of k transactions, $T = \{(A_i, p_i, B_i), i = 1, \ldots k\}$, to be conducted on the grid at the same time, the resulting power system operating condition can be computed from the dynamic system model,

$$dx/dt = f(x, z_T, u)$$
$$g(x, z_T, u) = 0$$

where x denotes the state variables including rotor angles, speeds and bus voltages and z_T represents the other system variables such as bus injections and line constants. The control variables including FACTS controllers are denoted by a vector u. Note that the k transactions $T = \{(A_i, p_i, B_i), i = 1, \ldots k\}$ need to be translated into a corresponding z_T vector. The transmission system operator is responsible for system security. The system operating constraints must be satisfied. There are two sets of system operating constraints: steady state and dynamic,

$h(x) \leq 0$ *(line flow and bus voltage limits)*
System dynamics constraints including rotor and voltage dynamics.

The system dynamics constraints listed above are not explicit. In practice, it is necessary to perform on- or off-line simulations to determine the system stability. The EPRI ETMSP (Extended Transient and Midterm Stability Program) is a very useful tool for simulation of the operating conditions. It is also common for the industry to perform off-line dynamic simulations to identify the interchange limits that will not lead to instability of the system. The available controls are limited. The FACTS control devices have their physical limits that can be described by

$$u_{min} \leq u \leq u_{max.}$$

Traditionally, simulations start with input data files. In a competitive environment, market conditions are described by a set of transactions including energy and ancillary services. Therefore it is necessary to develop software modules that translate these transactions into input files.

FACTS controllers may be located at various parts of the power grid. FACTS controllers can provide voltage and reactive power control (e.g., the STATCOM); they can afford impedance control (e.g., the TCSC, SSSC); and they can provide simultaneous active and reactive power flow control (e.g., the UPFC). It is also possible to provide power management on a transmission circuit as in the case of the IPFC [D35]. FACTS controllers can 'stretch' the transmission capabilities to meet the demand in the market. The control has to meet the system constraints as discussed in the last section. Conceptually, one can view the system constraints as an *n*-dimensional region inside which system stability and operating constraints are satisfied. In Figure 3-1, each axis in the 3-dimensional region can be used to represent the line flow on a tie line. Note that power companies have been using 'nomograms' based on off-line dynamic simulations. The multi-dimensional regions are generalized views of the same techniques. FACTS controllers and their parameters are selected so that the resulting tie line flows would not exceed the boundaries.

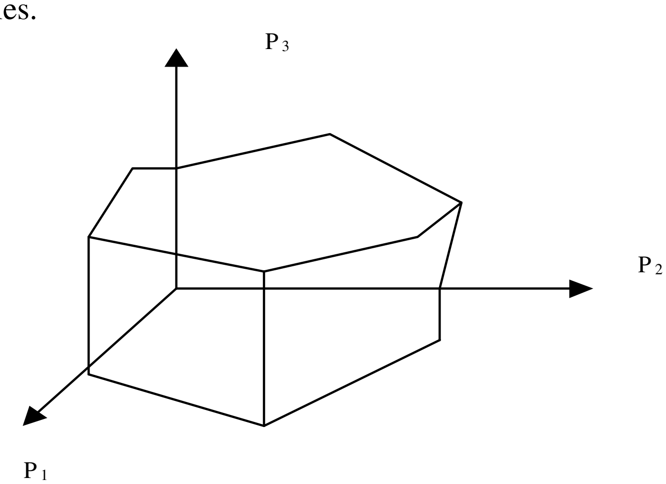


Figure 3-1
Illustration of transmission system constraints

As mentioned, the EPRI ETMSP is a very useful tool for simulation of rotor and voltage stability characteristics. However, the ETMSP requires the user to input the power system operating conditions and any contingencies to be considered for security assessment. The EPRI DIRECT program allows the user to calculate the stability margin for a specified fault condition. These tools are useful for calculation of the security boundaries illustrated in Figure 3-1. The major technical difficulty, however, lies in the multi-dimensional nature of the security boundaries. The simulation effort becomes prohibitive as the number of dimensions increases; one can imagine the number of points that have to be simulated to establish the boundaries in an n-dimensional region.

As illustrated in Figure 3-2, FACTS controllers should be used to widen the range of transmission access to participants in the grid. For a transmission operator, the widened access leads to better service or higher revenues. For given FACTS controller settings, it is necessary to evaluate the dynamic security of the system. The transmission reliability margin (TRM) can be determined by dynamic simulations. With effective FACTS control, the reliability margin can be reduced and therefore the available transfer capability is extended. Dynamic simulations can be performed with the EPRI ETMSP program. The ETMSP program incorporates both rotor and voltage dynamics.

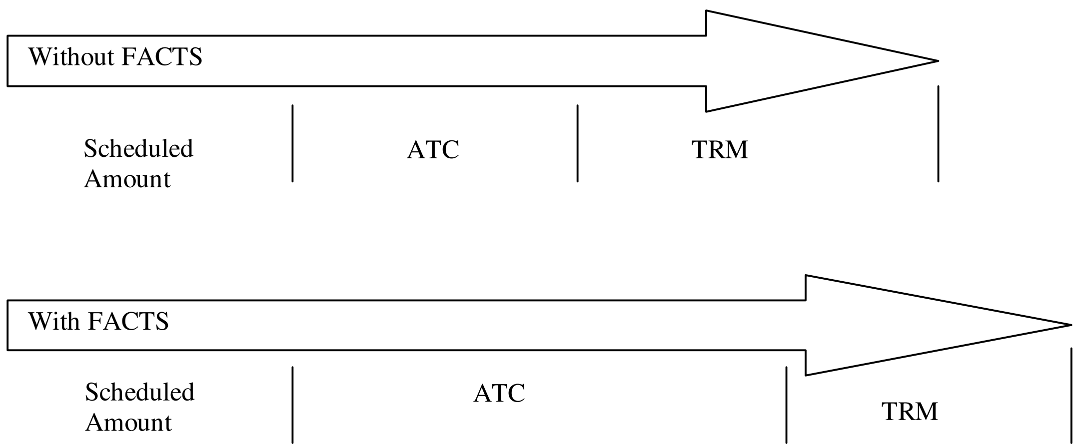


Figure 3-2
FACTS controllers extend ATC

Note that FACTS controllers are expected to increase the total transfer capability and reduce the transfer reliability margin due to better controls. As a result, the ATC for the transmission grid will be extended and therefore the transmission grid is better utilized. The dynamic security study is necessary to determine the amount of TRM that needs to be reserved for dynamic contingency conditions.

3.2 Injection Models of FACTS Controllers

A FACTS control can be modeled by power injections. The power injection models are convenient for system studies as the transmission system configuration or topology remains the same as FACTS controls are functioning. For a reactive power compensation device, such as an SVC, the equivalent load can be modeled as

$$Q = - k V^2$$

where V represents the bus voltage magnitude at the FACTS location and k is the equivalent susceptance of the FACTS element, in this case an SVC.

For a TCSC on a line from bus i to bus j, as shown in Figure 3-3, the device can be modeled as injections as well. Insert a variable reactance X_C in series with the line impedance X_L. Then the equivalent loads at the two buses are given by [J7],

Active power load

$$P_i = c(t)\,(1/X_L)\,V_i V_j \sin(\delta_i - \delta_j)$$
$$P_j = c(t)\,(1/X_L)\,V_i V_j \sin(\delta_j - \delta_i)$$

Reactive power load

$$Q_i = c(t)\,(1/X_L)\,[V_i^2 - V_i V_j \cos(\delta_i - \delta_j)]$$
$$Q_j = c(t)\,(1/X_L)\,[V_j^2 - V_i V_j \cos(\delta_j - \delta_i)]$$

where the factor $c(t) = X_C(t) / (X_L - X_C(t))$.

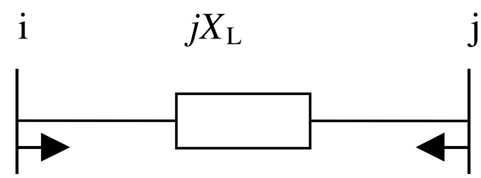


Figure 3-3
Injection model of TCSC

3.3 FACTS Controllers and Total Transfer Capability

By NERC definition [J8], the Total Transfer Capability is 'the amount of electric power that can be transferred over the interconnected transmission network in a reliable manner while meeting all of a specific set of defined pre-and post contingency system conditions.' Appendix B contains a summary of *all* definitions in reference [J8]. The calculation of TTC needs to take into account the system conditions such as load forecast, generation dispatch, transmission system configuration and scheduled transfers. Critical contingencies are also incorporated in the TTC calculations. The contingencies represent facilities outages that are most restrictive to the transfer. Depending on the system configuration and operating conditions, different power systems have different limiting factors. The TTC for an interconnected system should consider thermal, voltage and stability limits. These limits are evaluated based on the critical contingencies. It should be noted that the limiting factor of a system can change with time. In other words, the power transfer can be limited by different factors at different times due to the variations in system operating conditions.

Parallel path flows can occur in an interconnected system as a result of a power transfer. The parallel flows affect the transmission capability for entities in the interconnected system. The lack of transmission capability may then result in higher costs of transmission or inability to compete in the electricity market.

Conceptually, the effect of FACTS on TTC is clear. FACTS controllers allow power flow and voltage control that stretches the total transfer capability. For example, FACTS voltage controls can extend the voltage stability limit and power flow controls help to enlarge transmission bottlenecks. FACTS controllers also provide better controls when the system condition changes. Therefore the TTC is expected to increase as a result of FACTS installation. To quantify the cost-benefits of FACTS control logic, detailed analytical procedures for the interconnected system need to be developed.

3.4 FACTS Controllers and Transmission Reliability Margin

Based on [J8], NERC defined Transmission Reliability Margin as 'that amount of transmission transfer capability necessary to ensure that the interconnected transmission network is secure under a reasonable range of uncertainties in system conditions.' Appendix B contains a summary of definitions found in reference [J8]. The purpose of TRM is to handle the *uncertainties* due to the assumptions made in the calculation of the TTC and ATC. These uncertainties include transmission system configuration, location of future generations, weather, transmission facilities and the market conditions. Note that the time horizon for ATC calculation can be up to a year. Therefore, the uncertainties can have a significant impact on the ATC and TTC calculations. Also, the TRM can vary with time as the system conditions change.

FACTS controllers increase the amount of TRM for an interconnected system. FACTS controllers provide better control that increases the system's ability to deal with uncertainties. For example, the generation pattern can vary widely as a result of the market competition. This uncertainty was not as significant under the traditional vertically integrated structure. The uncertainty of generation pattern requires better control of the system in terms of the power flows and voltage profiles. Similar arguments can be made for other uncertainties, e.g., system topology, generation locations, weather.

To the best of our knowledge, there is no formal, systematic method to evaluate TRM. The NERC guidelines provide a direction, however. The role of FACTS needs to be incorporated into the analytical method.

3.5 FACTS Control Impact on ATC

Based on NERC's framework on Available Transfer Capability (ATC), the non-recallable ATC in operating and planning horizon is given by

$$NATC = TTC - TRM - NRES$$

where

TTC = Total transfer capability
$NATC$ = Non-recallable ATC
TRM = Transmission reliability margin
$NRES$ = Non-recallable reserved amount.

The total transfer capability is determined based on NERC document on 'Transmission Transfer Capability,' published in May 1995. The first contingency is taken into account in the calculation of TTC. As a result, TTC is based on the '*First Contingency Total Transfer Capability (FCTTC)*' or '*First Contingency Incremental Transfer Capability (FCITC).*' These two quantities are essentially the same; the only difference is that the latter uses a base case quantity as a reference.

The term TRM is an amount that ensures reliability of the interconnected transmission network. It is a transfer amount necessary to allow *uncertainty* in system conditions and the need for operating flexibility to ensure reliable system operation as system conditions change. Uncertainty exists in the future system topology, load demand, and power transactions. The uncertainty in the future transactions is particularly important in a competitive environment where many transactions take place.

The NERC documents suggest a procedure to determine the TTC, i.e., FCTTC, on an 'Area interchange' basis. Briefly, the steps to determine the TTC from Area A to Area B are:

- Start with a base case power flow
- Increase generation in Area A and increase load in Area B by the same amount
- Check the normal *thermal*, *stability* and *voltage* constraints
- Evaluate the first contingency event and ensure that the emergency operating limits are met
- When the emergency limit is reached for a first contingency, the corresponding (pre-contingency) transfer amount from Area A to Area B is the total transfer capability.
- If there is a special protection system, the remedial actions are taken into account in determining the post-contingency operating condition.

Note that the above procedure is general in the sense that it does not depend on the number of areas in the interconnection.

The NERC documents [J8] suggest a procedure to determine the TTC, i.e., FCTTC, on an 'Area interchange' basis. Briefly, the steps to determine the TTC from Area A to Area B are:

- Start with a base case power flow

- Increase generation in Area A and increase load in Area B by the same amount
- Check the normal thermal, stability and voltage constraints
- Evaluate the first contingency event and ensure that the emergency operating limits are met
- When the emergency limit is reached for a first contingency, the corresponding (pre-contingency) transfer amount from Area A to Area B is the total transfer capability.
- If there is a special protection system, the remedial actions are taken into account in determining the post-contingency operating condition.

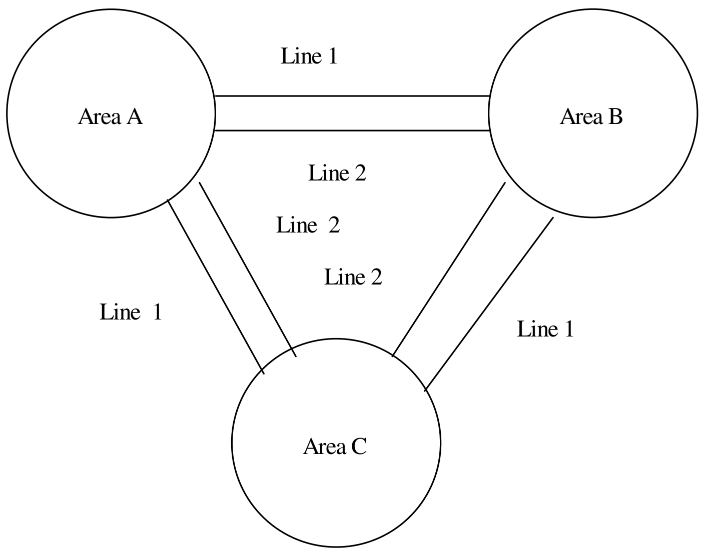


Figure 3-4
A three-area interconnected system

Example 3-1 Area exchange without FACTS controller

A three-area example, Example 6, in the NERC document [J8] demonstrates how the TTC is increased by use of a special protection system (SPS). The three area system is shown in Figure 3-4. In this example, a special protection system is designed to trip generators in Area A and to remove the same amount of pumping load from Area B simultaneously. The purpose of discussion here in this report is to demonstrate the role of a TCSC as a remedial control device.

The line flows data from the NERC 1995 document, "Transmission Transfer Capability," is repeated in Tables 3-1 and 3-2. Refer to the three area interconnected system in Figure 3-4.

Table 3-1
Line flows before and after line outage (without a special protection system, TTC from Area A to Area B = 786 + 786 + 107 + 107 = 1,786 MW, Example 3-1)

Lines	*Line flows before outage (MW)*	*Line flows after outage (MW)*
A → B No. 1	786	Outage
A → B No. 2	786	1,100
A → C No. 1	107	343
A → C No. 2	107	343
C → B No. 1	607	843
C → B No. 2	607	843

Table 3-2
Line flows before and after line outage (with a special protection system, TTC from Area A to Area B = 885 + 885 + 173 + 173 = 2,116 MW, Example 3-1)

Lines	*Line flows before outage (MW)*	*Line flows after outage (MW)*
A → B No. 1	885	Outage
A → B No. 2	885	1,100
A → C No. 1	173	343
A → C No. 2	173	343
C → B No. 1	673	843
C → B No. 2	673	843

Example 3-2 Area exchange with a FACTS controller

As mentioned, the above example can also be used to illustrate the use of FACTS as a *remedial control* to increase the TTC. Based on the injection model of a TCSC on a line from bus i to bus j, one inserts a variable capacitive reactance X_C in series with the line impedance X_L. Then the equivalent MW *loads* at the two buses are given by,

$$P_i = c(t)\,(1/X_L)\,V_iV_j \sin(\delta_i - \delta_j) \tag{3-1}$$

$$P_j = c(t)\,(1/X_L)\,V_iV_j \sin(\delta_j - \delta_i) \tag{3-2}$$

where the factor $c(t) = X_C(t) / (X_L - X_C(t))$.

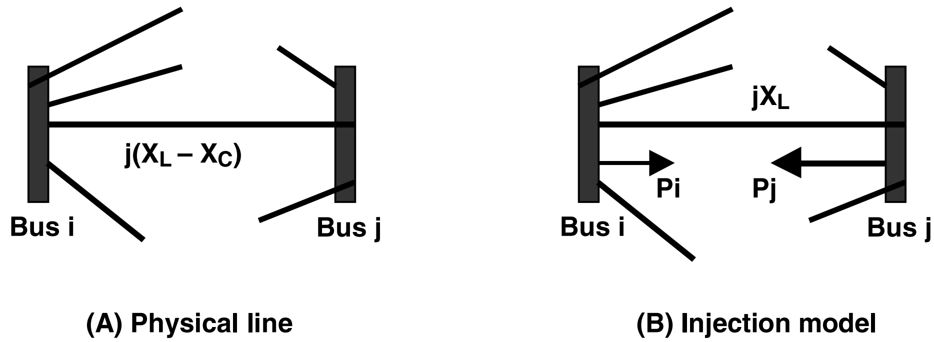


Figure 3-5
Loads Representing a TCSC

Consider an approximate (i.e., lossless line) form of the power flow equations. After the series capacitive compensation X_C is inserted, the *injection* into bus i is given by (note: this expression is for the active power flow *into* bus i from bus j),

$$P_{j\ \ to\ \ i} = \frac{1}{X_L - X_C} |V_i||V_j| \sin(\delta_j - \delta_i)\,. \tag{3-3}$$

This expression is for the compensated line. If it is desired to calculate the total injection into bus i from all remote buses isolating the term corresponding to the line that the FACTS controller will be sited,

$$P_{\text{into}\ \ i} = \sum_{not\ \ FACTS\ \ line} P_{lines} + \frac{|V_i||V_j|}{X_L - X_C}\sin(\delta_i - \delta_j)\,.$$

The final term represents the flow in the FACTS compensated line. Break this term into two portions,

$$P_{\text{into}\ \ i} = \sum_{not\ \ FACTS\ \ line} P_{lines} + \frac{|V_i||V_j|}{X_L}\sin(\delta_i - \delta_j) + \frac{|V_i||V_j|X_C}{(X_L - X_C)X_L}\sin(\delta_i - \delta_j)\,.$$

Move the last term to the left side to demonstrate that the FACTS controller is equivalent to an injection,

$$P_{\text{into}\ \ i} - \frac{|V_i||V_j|X_C}{(X_L - X_C)X_L}\sin(\delta_i - \delta_j) \ = \sum_{not\ \ FACTS\ \ line} P_{lines} + \frac{|V_i||V_j|}{X_L}\sin(\delta_i - \delta_j)\cdot$$

This represents a system with an added injection according to Equation (3-1) (note that the negative term on the left represents a load as depicted in Figure 3-5 (B)). To validate Equation (3-2) a similar procedure is used at bus j. Figure 3-5 (B) represents an injection model of the FACTS controller.

From the injection model represented by Equations (3-1) and (3-2), it is seen that, as *c(t)* varies, injections are increased or decreased by the same amount at the two ends. Note that the two injections are equal but with different signs. Suppose P_i is negative (i.e., fictitious generation) and P_j must be positive (i.e., fictitious load). As X_c is decreased, *c(t)* will also decrease. The fictitious generation at bus i modeling the TCSC is reduced while the fictitious load at bus *j* also becomes smaller. In other words, the generation and load at bus *i* and bus *j* are both reduced by the same amount.

Using the same data provided in the NERC document, the base condition has a 250 MW loop flow from Area A to B to C. *Without FACTS, the TTC is 1,786 MW from Area A to Area B, as shown in the NERC document.* This is assuming that there is a scheduled transfer of 1,000 MW from Area C to Area B. TTC calculation incorporates the first contingency. The critical line in this case is Line 1 from Area A to Area B. Following the outage, the line flow on Line 2 from A to B will reach the emergency thermal limit of 1,100 MW.

Now suppose a TCSC is installed on Line 2 from Area A to Area B and the corresponding (fictitious) generation at bus *i* on one side of Line 2 is 330 MW and the (fictitious) load on bus *j* side is also 330 MW in the normal operating condition. Note that a change in injections representing the TCSC does not imply that the physical generation or load is reduced since the actual generation and load in the three areas remain the same. The result of the TCSC change leads to a redistribution of power flows on the transmission lines, however. Suppose an outage of Line 1 from Area A to Area B occurs. If the TCSC on Line 2 is quickly adjusted to reduce the equivalent injection in bus *i* (Area A) and the injection at bus *j* (Area B) to zero, the resulting power flow on Line 1 and Line 2 from Area A to Area B would be 1,100 MW as shown in Table 3-1. *As a result, the TCSC increases the TTC from 1,786 MW to 2,116 MW.*

The physical phenomena in the SPS and TCSC cases are different. In the SPS case, the physical generation and load are reduced by 330 MW in order to avoid overloading Line 2 after Line 1 is lost. In the TCSC case, there is no change in the actual generation or load in Areas A and B. However, the impedance of Line 2 from Area A to Area B is changed by the TCSC control. The injection model of the TCSC makes it possible to view the impedance variation by the equivalent changes in injections. *The post-contingency power flows of the two cases are identical as the system topology, the line constants, and the net injections in all three areas are identical.* To clarify why the power flow solutions must be identical, note that the power network models for the SPS and the TCSC cases both use the line impedance of X_L for the line with compensation. The injections after the outage are identical as the same amount of reduction is applied to the two sides of the same line for both cases. Based on these observations, the post-contingency power flow solutions must be identical.

Uncertainty is accounted for through the TRM term. An example of how to handle the load uncertainty is to take the load range and evaluate the corresponding TTC for each scenario. Then, TRM can be found by examining the worst cases.

3.6 Summary

This chapter is concerned with system security assessment incorporating FACTS devices. The issues discussed in this chapter involve the system dynamics and how the transfer capabilities of interconnected power systems can be expanded through installation of FACTS devices. The results described in this chapter include:

- A general power system dynamic model incorporating FACTS controls
- Concepts for determination of the Available Transfer Capabilities (ATC) based on NERC guidelines
- Concepts for calculation of the Total Transfer Capabilities (TTC) with FACTS controls
- Feasibility of expanding TTC and ATC of the interconnected systems with FACTS controls
- A new technique to utilize a TCSC as a remedial control similar to a special protection system
- A new finding that allows a line impedance controller, e. g., a TCSC, SSSC, to be used in place of a special protection system (i.e., allows redistribution of system load upon a line outage contingency) *without* dropping either generation or load. This is significant because it permits higher ATC *without dropping generation*.

CHAPTER 4

INTELLIGENT SYSTEMS APPLICATIONS FOR FACTS CONTROLS

4.1 Intelligent System Techniques

Intelligent system techniques include expert systems, artificial neural networks, fuzzy logic, and evolutionary algorithms. Expert systems are software systems designed to emulate the problem solving behavior of human experts in narrow, specialized domains. Expert systems are sometimes referred to as knowledge-based systems. This is due to the fact that expert systems contain knowledge bases that incorporate domain knowledge or experience. Many expert system or knowledge based system applications to power systems have been proposed. The more successful applications to power engineering include fault diagnosis, system restoration and distribution systems. For FACTS applications, the system-wide control logic can incorporate expert knowledge in a knowledge base. This knowledge base can be used to assist system operators in identifying scenarios in which operator-initiated FACTS control is necessary. These controls may be needed as a result of system wide security or market considerations that may not be sensed by individual FACTS controllers. This knowledge base can be integrated with the control logic algorithms described in Section 4.2.

Artificial neural networks are natural tools for fast pattern analysis. A neural network uses neurons and their interconnections to form a signal analysis tool. Neurons generate outputs based on input signals and the internal functional model of the neuron. Generally, artificial neuron networks require a significant amount of training to achieve the appropriate parameter values. Many power system applications have also been proposed. The most successful application area is power system load forecasting. An EPRI product for load forecasting has been widely adopted by power companies. For FACTS applications, neural networks can be developed for control logic at the device level. Neural networks that receive information on voltage, power, etc. can identify the control settings of FACTS controllers.

Fuzzy logic is a technique to handle uncertainties. A fuzzy concept can be described by a membership function that ranges from 0 to 1 to indicate how precise the concept is. This uncertain concept can then become part of logic reasoning or neural computing. This gradual transition from complete precision to complete imprecision makes it possible to include fuzzy but useful knowledge in problem solving. Fuzzy logic applications to power systems include voltage control, load forecasting, equipment diagnosis, and distribution system applications. (An interesting fuzzy logic application is on washing machines.) For FACTS control logic, fuzzy membership functions can be used to describe uncertain system parameter or constraints for the optimal power flow formulations. Fuzzy logic–based controllers can be used to control power injections through FACTS parameter settings. This has been proposed for traffic control in transportation. Power system applications appear to be promising as well.

Genetic algorithms are computational techniques motivated by the natural law of 'survival of the fittest.' A pool of chromosomes can conduct crossover and mutation to form new chromosomes. However, the ones with higher fitness values will be retained. This process continues until the optimal or suboptimal solutions are found. Power system researchers have applied the genetic algorithms to scheduling problems such as unit commitment and economic dispatch. The genetic algorithms are not exhaustive search and therefore it is more efficient but there is no guarantee for the global optimality. For FACTS applications, the selection of FACTS locations and settings is a promising area. More details on this application will be described later in this section.

4.2 Selection of FACTS Locations and Settings

In general, it is desirable to identify the locations, types, and settings for FACTS in a transmission grid so that the transmission system can be fully utilized. The maximal transmission utilization is subject to the dynamic security constraints. The computational problem here is a complex one. The number of possible locations, types and settings and their combinations is large. For each combination, one needs to perform the ETMSP simulation to determine the level of system stability. Each scenario may require a few minutes of simulation time. Hence, it is infeasible to search exhaustively for the best possible combination of location, type and settings.

Intelligent system techniques include new heuristic search methods. Starting with the initial combination of the FACTS controller location and settings, one can simulate the system dynamics with tools such as ETMSP. Heuristics can be used to guide the search to determine the next combination. A brute force method would be to search with pre-specified step sizes and continue until the maximal access amount is achieved. A more refined method is to calculate sensitivity factors based on the ETMSP simulation results and use the sensitivity factors to identify the next combination for the search process. A genetic search technique would use a *fitness* measure to determine what combinations should be retained from the pool of combinations created based on *crossover* or *mutation*. This fitness measure needs to reflect the improvement in dynamic security due to adjustment of the FACTS location and settings. In Figure 4-1, the oval represents the pool of combinations of FACTS locations and settings. Each combination has a corresponding ATC value, which can be defined as the fitness value. The arrow pointing upward represents the ATC value of the transmission grid.

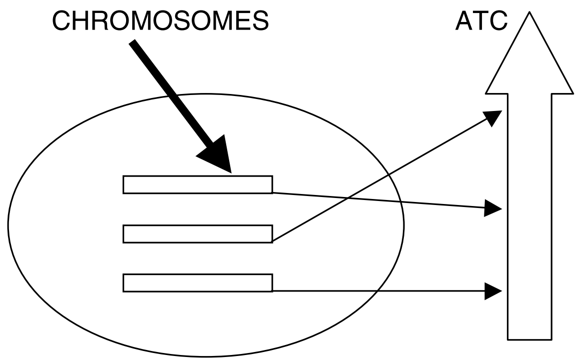


Figure 4-1
Genetic algorithm based search

To perform a genetic algorithm based search, one can model the types, locations, and settings by a string of binary numbers. For example, the device type can be represented by *M* binary digits. The possible locations can be represented by another *N* digits. The settings can also be modeled by *P* binary digits. The total length of *M*+*N*+*P* binary numbers then represents a chromosome:

011	*0011*	*11100000*
Type	*Location*	*Setting*

Clearly, the number of chromosomes depends on the complexity of the search problems. The algorithm can start with an initial population of chromosomes. The search algorithm conducts mutation and crossover and their variations to produce the next generation of chromosomes. For example, a mutation can replace one of the binary numbers:

011	*0011*	*11100000*	→	011	0010	11100000

Only the chromosomes with higher fitness values will be retained. For example, the type, location and settings of a chromosome can be evaluated by simulation tools such as ETMSP or optimal power flow to determine the corresponding ATC. In the above example, a digit 1 is changed to 0, indicating a different location is being chosen. Note that global optimality of the genetic algorithm is not guaranteed. Choice of the mutation and crossover techniques is important in providing good convergence characteristics. For FACTS controller type, location and settings, it may be useful to include empirical rules for mutation or crossover to increase the corresponding ATC value. An example is to move a FACTS controller closer to the location with more severe voltage problems. The move may result in a higher voltage stability margin, which is relevant for the ATC evaluation. However, it should be noted that heuristics may steer the search to 'local optimal' solutions. These features may be problem specific and therefore experimentation is needed to discover the best approach.

4.3 Summary

Intelligent system techniques include expert systems (or knowledge-based systems), artificial neural networks, fuzzy logic and evolutionary algorithms. All of them find useful applications associated with FACTS. These applications are different based on the diverse natures and capabilities of intelligent system techniques. This chapter discusses each of the techniques and its potential applications related to FACTS devices. The results of this chapter can be summarized by:

- Knowledge-based systems can serve as tools to assist system operators in identifying scenarios in which operator-initiated FACTS control is beneficial.
- Artificial neural networks can be used to calculate the appropriate control settings for FACTS devices.
- For FACTS control, fuzzy logic can be used to describe uncertain system parameters or constraints for the optimal power flow solutions. This is particularly useful for the calculation of transmission reliability margins associated with the ATC.
- Genetic algorithm techniques are proposed for heuristics-based search of locations and settings of FACTS devices that result in high ATC values between areas in an interconnected system.

CHAPTER 5

TRANSPORTATION MODELS AND STRATEGIES

5.1 The Transportation Concept

The term 'transportation' comes from the technology of city planning, railway and automobile transportation systems. The concept is fairly simple and based on the *conservation* principal that every thing that goes into a transportation system (e.g., super highway system, metro - railway system) must come out. For example, a network of superhighways that has four interchanges (depicted as A, B, C, and D in Figure 5-1. In this case, the highway system is a simple square, and the interchanges at A, B, C and D are depicted as arrows. The transportation concept is that the sum of the vehicles entering exchange A must equal (signs accounted for) the flows on roads AB and AC. Similarly the sum of the cars entering at B must equal the flows in AB and BD. No accounting is made for losses in the highways (e.g., a car goes off the road and impacts the count for that branch), or cars that might be involved in an accident and are never seen again.

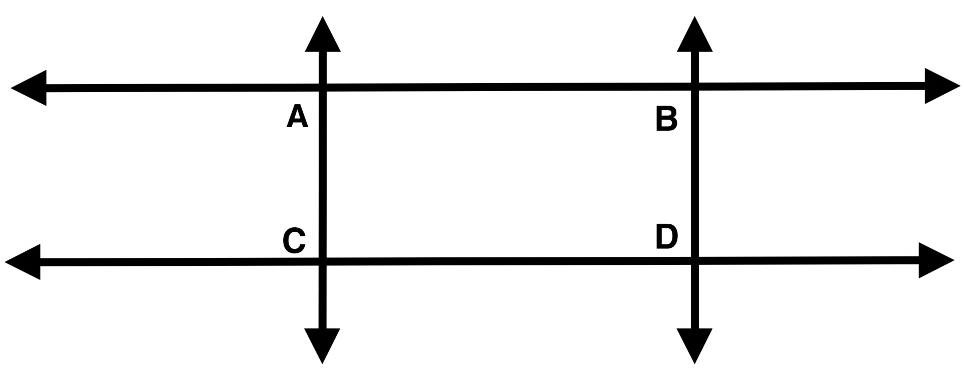


Figure 5-1
Superhighway system used to illustrate the generalized conservation concept of a transportation system

The transportation concept has two basic elements: nodal flows (e.g., the cars entering at A in Figure 5-1 and the branch flows (e.g., the flow in road AB). The conservation principal requires that whatever is flowing in the branches must equal the input flows. For the illustration above,

$$F_A + F_{BA} + F_{CA} = 0$$

$$F_B - F_{BA} + F_{DB} = 0$$

$$F_C - F_{CA} + F_{DC} = 0$$

$$F_D - F_{DB} - F_{DC} = 0$$

$$\begin{bmatrix} F_A \\ F_B \\ F_C \\ F_D \end{bmatrix} = \begin{bmatrix} -1 & -1 & 0 & 0 \\ 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & -1 \\ 0 & 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} F_{BA} \\ F_{CA} \\ F_{DB} \\ F_{DC} \end{bmatrix}.$$

In this case, the nodal injections are the singly subscripted F values and the branch flows are the double subscripted F values (where injection notation is used for the nodal injections and the notation F_{AB} refers to the flow from A to B metered at A). The coefficient matrix of the branch flow vector is termed the *incidence matrix* and the use of the letter L is common notation,

$$F_{node} = [L] F_{branch}. \tag{5.1}$$

Equation (5.1) is the basis of the transportation method.

In the subsequent sections, the transportation concept shall be used for the development of FACTS control logic. The elements of the transportation model that shall be used are:

- *Measurements* – the use of actual measurements in the system to fix flows. This input enhances accuracy. Measurements may be made in lines or at nodes. There may be multiple measurements of *the same or related parameters.*

- *Flow control* – this critical feature is included in the formulation in the form of fixing the required flow as required. The flow control mechanism is sometimes termed a flow gate and there are obvious parallels to various transportation system elements such as traffic lights, and freeway entrance controls.

- *Detouring* – this concept from actual vehicular transportation is useful as a control concept. Detouring is a form of line flow control, and this is included in the formulation.

- *Network models* – the network is modeled as a conservative system as outlined above. Losses can be accommodated by inclusion of flows and nodal inputs, sometimes dependant on other line flows.

- *Platooning* -- energy is transmitted in block amounts.

Inspection of the foregoing indicates some basic advantages and disadvantages of the transportation method. These are summarized in Table 5-1. The basic elements listed in this table do have additional complexities. For example, nonlinear models might be included as linearizations about an operating point – and therefore the problem may not be a real problem at all; the basic non-iterative nature of transportation solutions may be problematic because several different operating points may have to be modeled, and the calculation of the operating point may be iterative. Nonetheless, Table 5-1 gives a feel for the concept.

Table 5-1
Some basic advantages and disadvantages of the transportation method of analysis

Advantages	*Disadvantages*
Easy calculation (fast, sparse matrices, low memory requirements), can be done on-line	Does not model losses easily
Non-iterative, closed form of controls	Accuracy is questioned – may require adaptive control concept
Linear formulation	Change of system configuration requires reformation of incidence matrix (this can be done rapidly by accommodating only changed network links)
Models local phenomena well	Controls developed using this model may not be optimal because some nonlinearities and losses may not be accurately modeled
Lends itself to a wide variety of applications (e.g., electric power flow, automobile traffic, metro-rail)	Difficult to model nonlinear elements
Utilizes available measurements as inputs	May require a large number of measurements to enhance accuracy

5.2 Capabilities of Transportation Analysis

The formulation in Equation (5.1) is easily applied to AC electric power networks,

$$S_{bus} = [L]S_{line} . \tag{5.2}$$

In this case, the notation S refers to complex power, $P + jQ$. It is easy to show that incidence matrix L is formed in the ij position (corresponding to bus i and line j, where line j starts at bus k and ends at bus m, and the flow in line j is assumed to be measured at bus k

and flowing from k to m) as +1 when line j starts at k and –1 when line j ends at bus k. Otherwise L_{ij} is zero. Thus L is sparse. By this definition, L is rectangular (rows = the number of buses, columns = the number of lines) and always of deficient rank because the last row is a linear combination of the previous rows. Equation (5.2) can not be solved generally for the line flows because matrix L can not be inverted. But the pseudo-inverse of L can be used to give the least squares 'solution' to (5.1); that is, the several scalar equations in (5.2) can be matched as best as possible (in the least squares sense) using

$$[L]^{+}S_{bus} = S_{line}\,. \tag{5.3}$$

The superscript '+' refers to the pseudoinverse of a matrix (for example, see reference [J1], or refer to any information on Matlab which allows the calculation of the pseudoinverse by simply writing `Pinv(L);)`.

The utilization of the formulation in Equation (5.3) is limited – at least in the form in which this is written. This is the case because of the following factors:

- There are usually more lines than injection buses. Therefore the incidence matrix L has more columns than rows. This means that the estimation in (5.3) is generating more line flow estimates than there are relations (i.e., buses). This case is known as the underdetermined case.
- All estimates of the form of Equation (5.3) are subject to error. The error comes from error in the measurement of the bus injections, and neglect of certain factors (like losses). The error is made worse in the underdetermined case. These factors generally lead to unacceptably high error in the line flow estimates.
- The error can also be estimated from the eigenstructure of L. When the ratio of the largest to smallest singular value of L is large, estimates may have unacceptable error.
- There are ways to decrease the error, and even decrease the degrees of freedom (the number of lines minus the number of buses is called the degrees of freedom). Examples of techniques to accomplish this improvement are: inclusion of some line flow measurements; modeling of losses and other nonlinearities; modeling of line charging; utilization of a weighting matrix to enhance the best measurements and penalize the poor measurements; reduction of the size of the system; reduction of the number of lines in the system by equivalencing; development of intermediate buses to obtain additional relationships.

To review all the details of estimation using the formulation in Equation (5.3) is too lengthy. However, the main points are reviewed in Appendix A. The main capabilities of transportation power flow methods as applied to power systems and FACTS controllers in particular are:

- Controls signals can be rapidly calculated because the system analysis stems from a pseudoinverse of a matrix, and once this is done, the matrix is reused repeatedly.
- The controls are calculated in closed form – the method is not iterative
- The memory requirements of the calculation are low because the L matrix is sparse. This means that 'zero operations' are skipped and speed is enhanced as well.

- The general method of transportation solutions model local phenomena very well: that is, disturbances in either the steady state or transient sense are modeled well when the transient is local, and not severe. Unfortunately, the reverse is true as well: distant disturbances of large amplitude are not well accounted if they are outside the zone of high model detail. There may be simple 'fixes' to this difficulty, one of which is that the utilization of measurements accounts form model errors in real time.
- Electromechanical transients as well as steady state controls are easily accommodated. Thus the control is coordinated in the sense that stability as well as optimal dispatch applications are possible. This is a consequence of the fact that the electrical network usually does not contribute any dynamics to the problem. Only the rotating machines and loads contribute to the dynamics. Therefore, ignoring the dynamic nature of the network itself creates no problems.
- Line limits and line flow controls are easily included because in the transportation method, line flows are system states.
- The method can accommodate full AC solutions including active and reactive flows. However, the active and reactive losses in the network itself are a clear problem area. Because the transportation method is strictly linear, terms like $|I|^2R$ and $|I|^2X$ can not be included. There may be ways to obviate the problem – and a few are discussed later in this chapter, but this difficulty is a clear disadvantage of the method.
- Examples of the concepts of solution and control using transportation methods are shown in Appendix A.
- The accuracy of the calculated control signal depends on the eigenstructure of the incidence matrix *L*. While this can create problematic conditions, robustness can be built into the controller by utilizing a large number of measurements of the system, and by innovative linearization in stages.
- It is a simple matter to show that the formulation in Equation (5.3) is equivalent to an unbiased state estimation. The term unbiased in this context refers to the fact that the equation $A\hbar = b$ is 'solved' for $\hbar$ by minimizing the error in each of the scalar equations in the expression $A\hbar = b$ on an equal basis. That is, the residual

  $$J = (A\hbar - b)^t(A\hbar - b)$$

  Is minimized by selecting $\hbar$ as

  $$\bar{\theta} = A^+b.$$

  The bar over $\hbar$ refers to the fact that this is an estimated value. If J were zero, $\bar{\theta}$ would be simply $\hbar$. The formulation indicated is the usual unbiased estimator [J2]. If the residual is biased in favor of better measurements and relations, that is, if the residual J is weighed for some equations and less weighed for others, then the residual is rewritten as

  $$J = (A\hbar - b)^tW(A\hbar - b) \tag{5.4}$$

  Where W is a weighting matrix. If W is diagonal, the diagonal elements are large when the corresponding equation is to be heavily weighted. Equation (5.4) is the biased estimator. It is a simple matter to show that the corresponding estimated solution is

$$\bar{\theta} = (\sqrt{W}A)^{+}\sqrt{W}b\,. \tag{5.5}$$

5.3 Steady State Control for FACTS Controllers Using Transportation Methods

The basic formulation above is rewritten for convenience,

$$\begin{bmatrix} S_{bus1} \\ S_{bus2} \\ \cdots \\ S_{busm} \end{bmatrix} = \begin{bmatrix} L_{11} & L_{12} & \\ L_{21} & L_{22} & \\ & \cdots & \\ & & L_{km} \end{bmatrix} \begin{bmatrix} S_{line1} \\ S_{line2} \\ \cdots \\ S_{Linek} \end{bmatrix}. \tag{5.6}$$

There are m buses and k lines in this model. In order to include FACTS controls operating in the sinusoidal steady state (i.e., $t > 17$ ms, average power considered), Equation (5.6) should be augmented by additional equations and modified to represent an actual interconnected power system:

- Measurements of active and / or reactive power at some buses
- Measurements of line flow active and / or reactive power at selected lines
- Partitioning of the bus injection vector into a controlled subvector (i.e., the injections are to be controlled at these buses), and a subvector that is uncontrolled. This partition may be active power alone, or reactive power alone, or a combination of both.
- Partitioning of the line flows into subvector that represents the line flows that are to be controlled, and a subvector of uncontrolled line flows. This partition may be active power alone, or reactive power alone, or a combination of both.
- Partitioning the line vector to contain a subvector corresponding to lines with FACTS controllers
- Identical parallel lines may be accommodated by an expression of the form $S_{line\ i} = S_{line\ j}$, or the two (or more) lines may be equivalenced into a single circuit
- Care should be taken in partitioning and organization of the state estimation problem because, unlike simple solution of simultaneous equations, the scaling of the state equations will have a significant impact on the solution of the corresponding state estimation problem.

Each of these considerations (termed *inclusions*) is *augmented* to the transportation model. The *inclusions* require partitioning of the line flow and bus injection vectors as follows,

S_{bus} =

Bus injections at buses with desired, set values
Bus injections at instrumented buses
Other bus injections

S_{line} =	Line flows in lines with desired set values
	FACTS controlled line flow (FACTS control setting)
	Line flows in measured lines
	Line flows in other lines

Using the notation

$$S_{bus} = \begin{bmatrix} A \\ B \\ C \end{bmatrix} \qquad\qquad S_{line} = \begin{bmatrix} E \\ F \\ G \\ H \end{bmatrix}$$

to represent the partitioning, the dimensions of the partitions of the line flow and bus injection vector are as indicated in Table 5-2. Then Equation (5.6) is rewritten as follows taking into account the inclusions,

$$\begin{bmatrix} A \\ B \\ C \end{bmatrix} = \begin{bmatrix} L_{AE} & L_{AF} & L_{AG} & L_{AH} \\ L_{BE} & L_{BF} & L_{BG} & L_{BH} \\ L_{CE} & L_{CF} & L_{CG} & L_{CH} \end{bmatrix} \begin{bmatrix} E \\ F \\ G \\ H \end{bmatrix}$$

$$[B] = M_b$$

$$[G] = M_l$$

$$[A] = D_b$$

$$[E] = D_l$$

where M_b, M_l, D_b, D_l refer to the bus and line measurements and bus and line desired (set point) power flows. Combining these relations into one matrix formulation gives (let I refer to the identity matrix)

$$\begin{bmatrix} I & 0 & 0 & -L_{AE} & -L_{AF} & -L_{AG} & -L_{AH} \\ 0 & I & 0 & -L_{BE} & -L_{BF} & -L_{BG} & -L_{BH} \\ 0 & 0 & I & -L_{CE} & -L_{CF} & -L_{CG} & -L_{CH} \\ 0 & I & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & I & 0 \\ I & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & I & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} A \\ B \\ C \\ E \\ F \\ G \\ H \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ M_b \\ M_l \\ D_b \\ D_l \end{bmatrix} \tag{5.7}$$

Equation (5.7) is 'solved' in the biased case as

$$\begin{bmatrix} \overline{A} \\ \overline{B} \\ \overline{C} \\ \overline{E} \\ \overline{F} \\ \overline{G} \\ \overline{H} \end{bmatrix} = \left(\sqrt{W} \begin{bmatrix} I & 0 & 0 & -L_{AE} & -L_{AF} & -L_{AG} & -L_{AH} \\ 0 & I & 0 & -L_{BE} & -L_{BF} & -L_{BG} & -L_{BH} \\ 0 & 0 & I & -L_{CE} & -L_{CF} & -L_{CG} & -L_{CH} \\ 0 & I & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & I & 0 \\ I & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & I & 0 & 0 & 0 \end{bmatrix} \right)^{+} \sqrt{W} \begin{bmatrix} 0 \\ 0 \\ 0 \\ M_b \\ M_l \\ D_b \\ D_l \end{bmatrix} \tag{5.8}$$

If an unbiased estimate is desired, replace the weighting matrix *W* by *I*. In Equation (5.8), the solution for subvector *F* is the FACTS control signal.

Table 5-2
Dimensions of subvectors in the partitioned line flow and bus injection vectors

Subvector	*Dimension*
A	Number of buses with a desired (set point) power injection, N_A
B	Number of buses at which injection is instrumented, N_B
C	Other buses, N_C

Subvector	*Dimension*
E	Number of lines with a desired (set point) power flow, N_E
F	Number of lines with a FACTS controller, N_F
G	Number of lines with a power flow measurement, N_G
H	Other lines, N_H

Inclusion of reactive power flow

In Equation (5.8) and Table 5-2, discussion focuses on active power flow. The formulation is for an active power flow control averaged over one cycle (or more) in real time. The question of inclusion of reactive power flow control is now visited. The formulation above is easily augmented by a set of transportation conservation equations for reactive power flow. That is, the line flows and bus injections of reactive flow can be added. The equations are omitted but are in exactly the same form as Equation (5.8) and can accommodate line reactive flow settings (as in the application of a UPFC) as well as bus injections (as in the application of an SVC). The subject of the inclusion of reactive power flow and reactive power flow controls is discussed further in Appendix C (and examples are given there).

Voltage regulation features

Equation (5.8) and Table 5-2 relates to the control of active power; however, it is possible to include the control of bus voltage magnitudes. This voltage regulation concept is essentially the inclusion of FACTS control parameters in a power flow study with selected bus voltages fixed to a desired setting. To accomplish this, Equation (5.8) needs to be modified to include the calculation of bus voltage magnitude. This is done by including the decoupled power flow equations,

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \approx \begin{bmatrix} \frac{\partial P}{\partial \delta} & 0 \\ 0 & \frac{\partial Q}{\partial |V|} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix}.$$

It is also possible to include the off-block diagonal terms. The Jacobian matrix entries are precalculated and fed to the FACTS control logic, and these are used to fix bus voltages as desired. The subject of voltage regulation is further discussed with examples in Appendix C.

Changed cases – the calculation of FACTS control settings

The forgoing defines the term *inclusions* as equations that are added to the system equations to augment the solutions. This is done to enhance estimation accuracy. Consider the case of an operative power system in a 'base case'. Further consider that it is desired to force the line flows in certain buses to be a different value – through the setting of FACTS controllers imbedded in the system. Then the problem becomes one of changing the base case to a 'changed case' as depicted in Figure 5-2. The objective is to calculate the FACTS control signal to obtain the desired changed case. Obviously, this control is independent of the base case. Hence one needs to write only the system equations plus inclusions for the changed case. These are shown in Table 5-3. In Table 5-3, note that the 'floating bus' is the swing bus – usually there is only one such bus in the system, although it is a simple matter to have any number of swing buses.

Base case			*Changed case*
	FACTS line		*FACTS line**
	*Fixed bus load**	*Same value* →	*Fixed bus load**
	Floating lines		*Floating lines*
	Floating buses		*Floating buses*
	*Measured lines**		*Measured lines**

*Known values

Figure 5-2
Base and changed cases

Table 5-3
Equations used for the calculation of the changed case depicted in Figure 5-2*

Number of equations	*Number of unknowns*	*Type*	*Form of expression*
	N_F	FACTS settings	
N_G		Measured lines	G = measured value
N_E		Desired line flows	E = desired values
N_A+N_B		PQ and PV buses	A = given value, B = given value
	1	Swing bus**	
	N_H	Line flows	
$N_A + N_B + 1$ = *number of buses*		Conservation of power	$S_{bus} = [L]S_{line}$

*The exemplary formulation is for a UPFC application, N_F UPFCs are used
**One swing bus assumed, $N_C = 1$

The solution of the case depicted in Table 5-3 is found from the manipulation of

$$\begin{bmatrix} A \\ B \\ C \end{bmatrix} = \begin{bmatrix} L_{AE} & L_{AF} & L_{AG} & L_{AH} \\ L_{BE} & L_{BF} & L_{BG} & L_{BH} \\ L_{CE} & L_{CF} & L_{CG} & L_{CH} \end{bmatrix} \begin{bmatrix} E \\ F \\ G \\ H \end{bmatrix}$$

$$[B] = M_B$$

$$[G] = M_G$$

$$[A] = M_A$$

$$[E] = D_E$$

where M_G is the measured values of vector G; M_B is the measured values of vector B; M_A is the measured values of vector A; and D_E is the desired flows in vector E. Vectors M_B, M_G, M_A, D_E are known. The manipulation gives

$$\begin{bmatrix} 0 & -L_{AF} & -L_{AH} \\ 0 & -L_{BF} & -L_{BH} \\ 1 & -L_{CF} & -L_{CH} \end{bmatrix} \begin{bmatrix} C \\ F \\ H \end{bmatrix} = \begin{bmatrix} -M_A + L_{AE} D_E + L_{AG} M_G \\ -M_B + L_{BE} D_E + L_{BG} M_G \\ L_{CE} D_E + L_{CG} M_G \end{bmatrix}$$

and the weighted transportation solution is

$$\begin{bmatrix} C \\ F \\ H \end{bmatrix} = \left[\sqrt{W} \begin{bmatrix} 0 & -L_{AF} & -L_{AH} \\ 0 & -L_{BF} & -L_{BH} \\ 1 & -L_{CF} & -L_{CH} \end{bmatrix} \right]^{+} \sqrt{W} \begin{bmatrix} -M_A + L_{AE} D_E + L_{AG} M_G \\ -M_B + L_{BE} D_E + L_{BG} M_G \\ L_{CE} D_E + L_{CG} M_G \end{bmatrix} \tag{5.9}$$

Subvector F is the required FACTS controller setting.

Equations and unknowns in the changed case

The number of equations in the changed case is listed in Table 5-4. In general, this is an overdetermined system, and the transportation solution should be a relatively accurate solution. The actual accuracy is dependent on the eigenstructure of the state estimation matrix. Although this can not usually be predetermined, for a given numerical example, thew accuracy and confidence in the solution is readily determined. This is discussed in Appendix A.

Table 5-4
Number of equations and unknowns in the changed case solution for the FACTS control signal (one swing bus assumed)*

Number of equations	$N_A + N_B + 1$
Number of unknowns	$1 + N_F + N_H$
Equations - unknowns	$N_A + N_B - N_F - N_H$

*The exemplary formulation is for a UPFC application, N_F UPFCs are used

Alternative formulation

An alternative formulation to the steady state FACTS controller using transportation methods is given here. Because the foregoing is a least squares estimator, the solution is not a true solution in the mathematical sense of zero residual. In fact, the residual function J will generally not be zero, and the value of J can be used as a measure of the confidence in the solution. If the errors are created by Gaussian process noise, a simple formulation of the confidence based on the chi-squared test is commonly used. This is described in many places – for example reference [J2]. An alternative formulation is created by removal of the subvectors B and G in Equation (5.7). These are measured values and if the measurement is to be weighted infinitely (i.e., simply accepted as fact), then the subvectors B and G are not state variables at all, and they are not represented in $\hbar$. The development parallel that given above, and the result is,

$$\begin{bmatrix}\overline{C}\\ \overline{F}\\ \overline{H}\end{bmatrix} = \left(\sqrt{W}\begin{bmatrix}0 & -L_{AF} & -L_{AH}\\ 0 & -L_{BF} & -L_{BH}\\ I & -L_{CF} & -L_{CH}\end{bmatrix}\right)^{+}\sqrt{W}\begin{bmatrix}L_{AG}M_l - D_b + L_{AE}D_l\\ M_b + L_{BG}M_l + L_{BE}D_l\\ -L_{CG}M_l + L_{CE}D_l\end{bmatrix}. \qquad (5.10)$$

In Equation (5.10), I is the identity matrix, and $\overline{F}$ is the estimate of the FACTS control signal.

The application of Equations (5.8) - (5.10) to FACTS controllers is discussed in connection with a hierarchical structure in Section 5.6. In the use of Equations (5.8) - (5.10), it is important to know the eigenstructure of the matrix that is pseudoinverted. The dimensions of this matrix are listed in Table 5-5. An example of the application is shown in Appendix A which also contains remarks on the implementation of these controls. Figure 5-3 is a pictorial of how the steady state FACTS controller would be implemented.

Table 5-5
Dimensions of the coefficient matrix for state estimation / transportation solution using Equations (5.8) - (5.10): exemplary values (exemplary formulation is for a UPFC application, N_F UPFCs are used)

	Equation (5.8)	Equation (5.9)¶	Equation (5.10)
Dimensions of coefficient matrix*	$[N_A+N_B+N_C+N_E+N_G+N_H]$ by $[2N_A+2N_B+N_C+N_G+N_E]$	$[N_C + N_F + N_H]$ by $[N_A + N_B + 1]$	$[N_C+N_E+N_H]$ by $[N_A+N_B+N_C]$
Example**	2400 by 2428	376 by 1000	972 by 1000
Equations – unknowns = *degrees of freedom*	28	624	28

* The dimension of the coefficient matrix is the dimension of the pseudoinverse matrix
** The example shown is for a 1000 bus system with 1400 lines. The system has three buses with a required (set point) injection; 400 buses are instrumented by telemetering; 25 lines have a desired (set) power flow; 1000 lines have instrumented active power flow; and three FACTS controllers are present.
¶ One swing bus is assumed

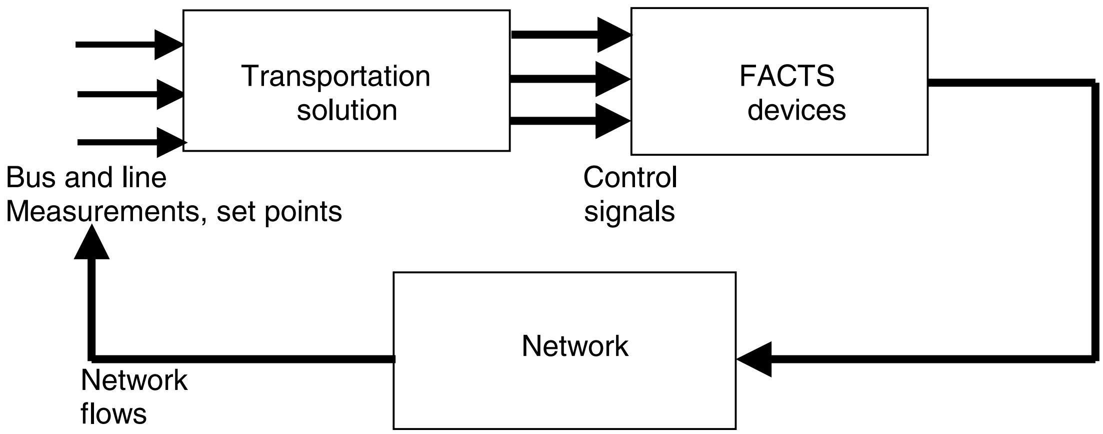


Figure 5-3
Implementation of a steady state FACTS controller using the transportation method

Degrees of freedom

In all state estimation applications, and the transportation method is essentially a state estimator, it is best to have far more measurements than quantities to be estimated. The difference in the number of measurements and the number of estimates may be viewed as a measure of degrees of freedom. Formulated as,

$$\textit{Degrees of freedom} = \textit{number of measurements} - \textit{number of estimates},$$

the larger the degrees of freedom, the better. For example, examining Table 5-5 for Equations (5.8) and (5.10), one finds that,

$$\textit{Number of estimates} = N_A + N_B + N_C + N_E + N_F + N_G + N_H$$

$$= \textit{number of lines} + \textit{number of buses}$$

$$\textit{Number of measurements and physical equations} = 2N_A + 2N_B + N_C + N_G + N_E.$$

Therefore the degrees of freedom are,

$$\textit{Degrees of freedom} = N_A + N_B - N_F - N_H.$$

For Table 5-5 for the case of Equation (5.9), one finds that

$$\textit{Degrees of freedom} = N_A + N_B - N_F - N_H.$$

The three cases of determination of the estimates are shown in Table 5-6. It is desired to be as overdetermined as possible to obtain the highest accuracy.

Table 5-6
Determination of estimates using a transportation method

Case	*Degrees of freedom*	*Number of measurements, estimates*
Overdetermined	Positive	Measurements > estimates
Critically determined	Zero	Measurements = estimates
Underdetermined	Negative	Measurements < estimates

5.4 Transient Controls Based on the Transportation Method

The basic foregoing discussion form the sinusoidal steady state case also applies to the transient case. This is a correct statement if the transient case is limited to time horizons of sufficient length to allow the assumption of average power (i.e., averaging over a cycle or more of the AC wave). Figure 5-4 shows the very basic transmission of power across inductive reactance *jx*. For the elementary lossless case, the power averaged over one cycle is,

$$P_{ab} = \frac{|V_a||V_b|\sin(\delta)}{x}$$

A similar expression is easily written for the lossy case. This transport flow model is accurate in the sinusoidal steady state case or for transients of duration longer than one cycle. That is, if the power flow is measured by an averaging instrument, and the average is taken over either an integer number of cycles or a very large number of cycles, the calculation of the average power flow in the line will be correct.

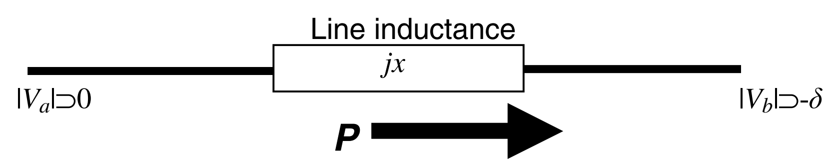


Figure 5-4
Power flow in an inductive reactance *jx*

For the cited case of an integer number of 1 to 5 cycles (in a 60 Hz system), or a large number of cycles (T > 16.7 ms), FACTS controls may be calculated using the results from the sinusoidal steady state section above. For this application, the assumption of average power is made in measurements and controls.

The implementation of the transient FACTS controller using transportation methods is illustrated in Figure 5-5. In this pictorial, a sample interconnected system is illustrated with control areas 1, 2, 3, and 4 highlighted. The flows of power into control area 4 are singled out for discussion. To implement the FACTS controller in area 4, measurements are made of the key tie lines and intertie buses to area 4. Also indicated in Figure 5-5 is the potential or auxiliary signals developed for power system stabilizers in a unified dynamic controller.

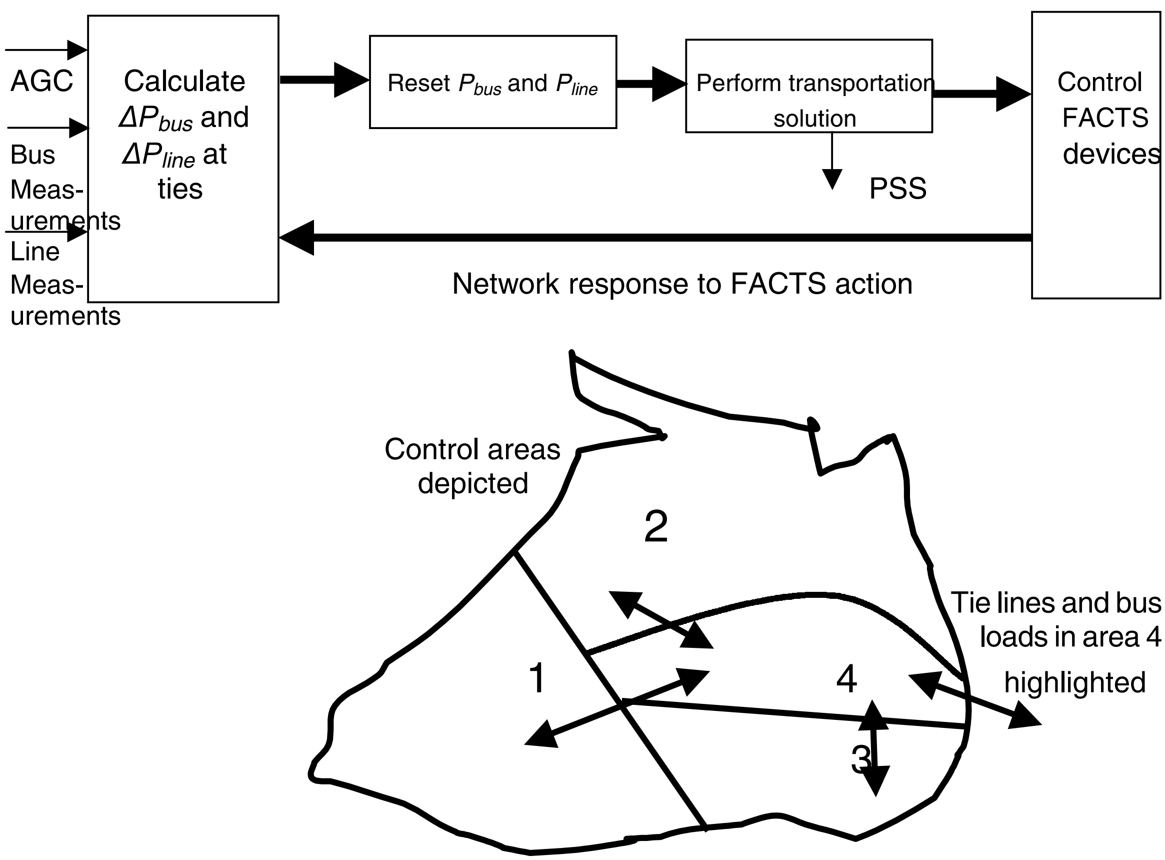


Figure 5-5
Implementation of a transient FACTS controller using transportation methodology

The foregoing indicates that the transportation method is essentially an average power method, and therefore the method lends itself mainly to steady state operation. However, there are operating conditions that can be detected that will lead to the mode of operation that FACTS controls should enhance damping. The detectors for this mode are:

- Excessive key line loading
- Certain relaying operations
- Excessive generator unit loading
- Rapid loading increase
- Manual directives.

In these cases, the FACTS controller needs to transfer from the sinusoidal steady state to the dynamic performance enhancement mode. One strategy in the dynamic performance mode is the calculation of unit reduced loading, line reduced loading, and reduction in operating bus voltage phase angles. These issues are essentially sinusoidal steady state issues, and the transportation concept can be applied. The logic, then, is to identify the transient performance enhancement mode, calculate the required line or bus loading change, calculate the FACTS control setting (and direct FACTS controller signal), and to apply that signal. This concept is shown in Figure 5-6.

5.5 Inclusion of Line Losses

The transportation method does not include nonlinear effects such as line losses. However, it is permitted to add an additional step to the algorithm: the method can be modified to accommodate line losses. The concept is to run a base case transportation study as indicated above, calculate the line flows in lossy lines, and to calculate the losses in each line. Then one-half of the losses of each line are included as a load at the line terminals. The concept is indicated in Figure 5-7. After the line losses are included as indicated, the transportation study is repeated. Obviously, this will not give the correct result when the line losses are very high and materially effect the line flows. However, with active power losses in the 0 – 3% range, the method works satisfactorily.

The indicated method to include line losses does result in an error in the on-line calculation of FACTS controls. But, since the controls are on-line, and changing with measured conditions, the line loss errors cause only a minor dither in the control signal. That is, the control is applied, and the response is not as expected, thus resulting in further control. The process reoccurs on-line until the error dissipates to zero.

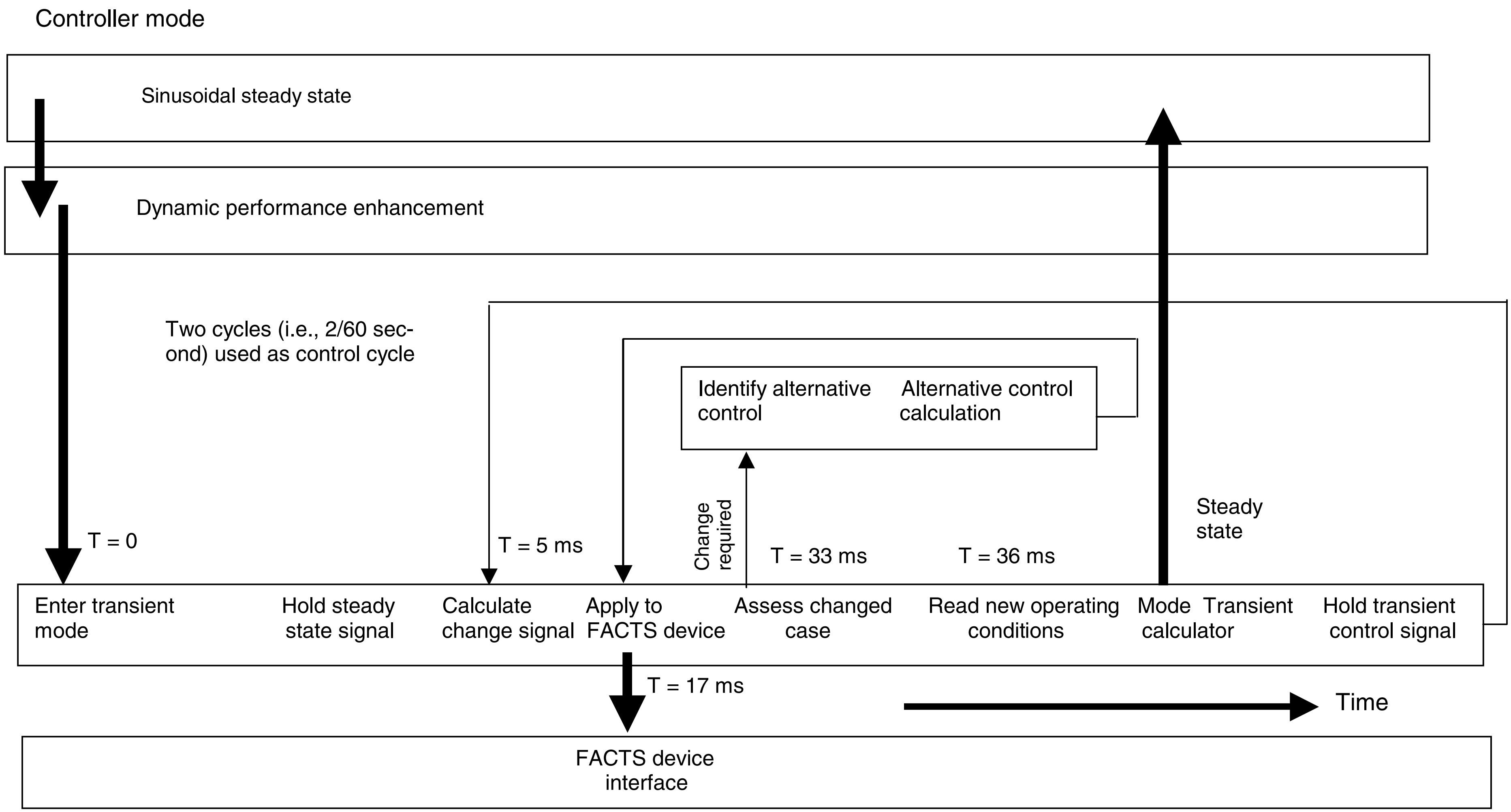


Figure 5-6
Depiction of the control logic for a transportation method calculation of FACTS control signals

5.6 A Hierarchical FACTS Control Structure Based on Transportation Methods

The utilization of transportation methods in a hierarchical control structure may be based on the concepts indicated in Chapter 2. The most suitable portions of the control structure for transportation methods is the steady state higher level structures (e.g., the wide area and control area steady state segments of the control hierarchy). This is depicted in Figure 5-8. The implementation of a transportation based wide area, sinusoidal steady state FACTS controller is shown in Figure 5-9. In this figure, logic is included to determine the mode of the controller (i.e., steady state, transient, and which control objectives are utilized).

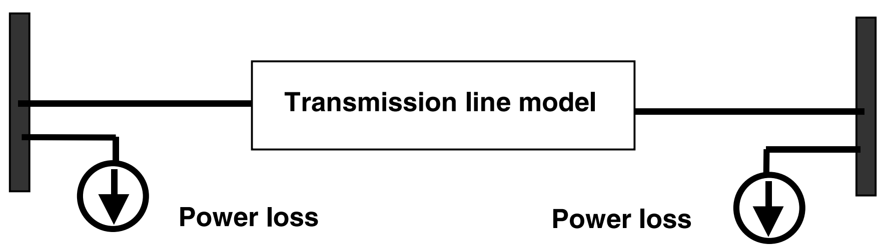


Figure 5-7
Inclusion of line losses in a transportation power flow study and on-line FACTS control

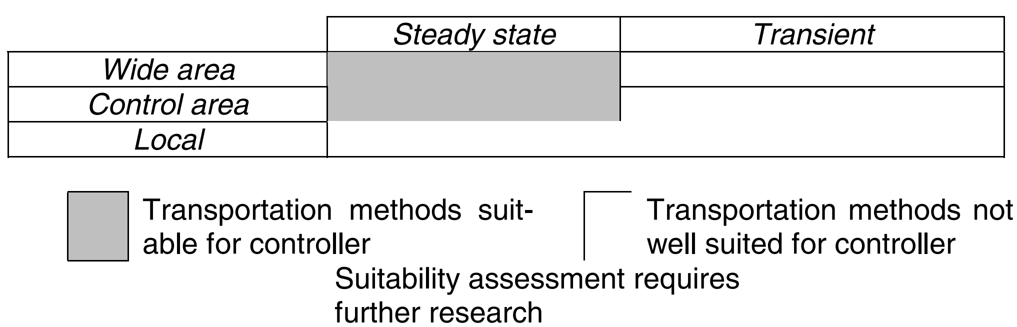


Figure 5-8
Hierarchical structures most suitable for transportation solutions

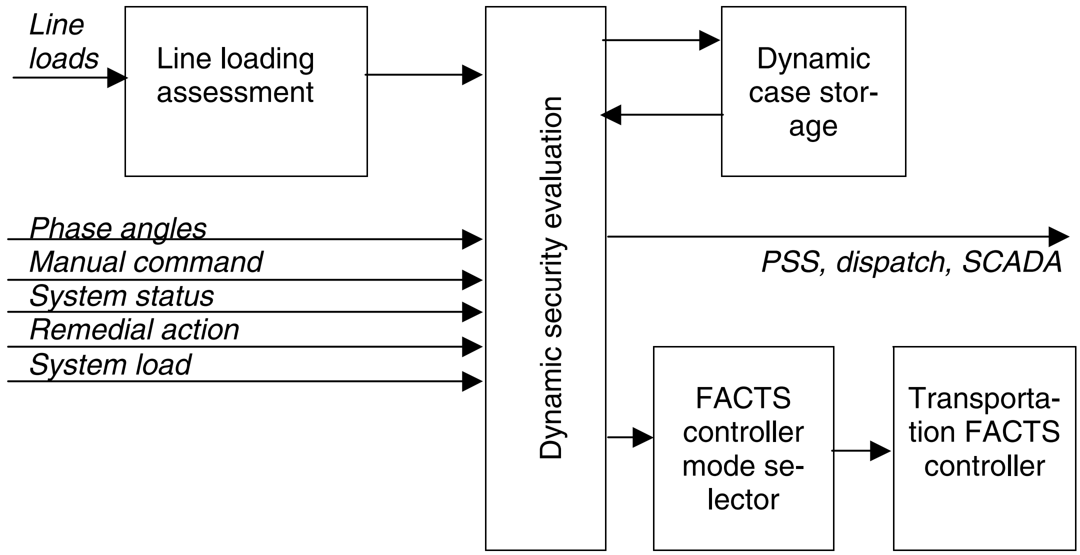


Figure 5-9
Transportation method used in the sinusoidal steady state FACTS controller at the wide area and control area hierarchies

5.7 Limitations of Transportation Methods

The main limitations of the transportation method for rapid power system solution, and application to FACTS controller hierarchy are:

- Limitation of transient time to integer number of cycles (for short transients) to about 17 ms
- Approximate inclusion of losses, resulting in an iterative dynamic response on-line. Similarly, nonlinear effects are not modeled and there will be an iteration required in the control to accommodate these effects.
- The method may not satisfy the Kirchhoff laws, and therefore the control generated on line may be iterative
- The method does not directly address voltage collapse and var support. If it is desired to incorporate these issues into the control, it is necessary to reformulate the state vectors to include bus voltage, and this becomes much more complex.

The advantages of the method are its speed of solution and therefore its suitability for an on-line controller. Other advantages are that a coordinated control is readily implemented using transportation methods; circuit operating changes (e.g., line out of service, line added to service) can be accommodated by performing one singular value decomposition of the state estimation matrix, and performing changed cases on the lower and upper rectangular matrices.

5.8 Summary

Transportation methods are based on the conservation of power. These expressions alone do not give sufficient equations for the development of FACTS device control signals, but in combination with bus load measurements, and line power flow measurements, sufficient degrees of freedom are available for an accurate control strategy solution. The method is easily programmed in higher level programming languages, it has been shown to be valid for small examples, and it has an adaptive nature which should allow for the accurate calculation of a control signal. The main limitation of the method is in accuracy of the calculation of the control signal; this can be controlled by augmenting the method with measurements and careful design of the placement of the measurements. The main advantage of the method is in calculation speed and the fact that relatively little memory is needed for the calculation. The method is best suited for a sinusoidal steady state solution of the FACTS control problem, although transient stability enhancement is also possible.

CHAPTER 6

FAST SYSTEM STUDIES AND APPLICATIONS TO FACTS CONTROLLERS

6.1 Types of Fast System Analyses

The on-line requirements of FACTS controllers in the sinusoidal steady state and the transient case require that circuit analysis be done rapidly., That is, a full dynamic security study is infeasible as is a full power flow study. For this type of application, fast analysis methods are proposed. Typical requirements are listed in Table 6-1. Fast analysis methods proposed for FACTS controllers are listed in Table 6-2. Not listed in the table are transportation methods that are covered in the foregoing chapter in detail. The main techniques for fast calculation are also depicted in the web diagram in Figure 6-1.

Table 6-1
Approximate response time requirements for FACTS controllers for various control regimes

Type of control	Estimated response time requirement	
	Steady state requirement	*Transient requirement*
Power flow control	Several cycles (e.g., 150 - 300 ms)	Rapid, on-line tracking capability. Realistic estimates are in the quarter cycle range (e.g., 3 - 10 ms)
Voltage control	Several cycles, but faster response time as compared to power flow control to track load variation (e.g., 50 – 200 ms)	Quarter cycle requirement as evidenced by transient voltage restorer applications (e.g., 3 - 10 ms)
VAr control	50 – 200 ms	Applications uncertain, estimated at 3 - 10 ms

6.2 Fast Methods and Their Suitability as FACTS Controllers

The requirements for calculation of FACTS controls fall into two main categories: the slow and the fast. In the slow category are the signals needed for power flow control and OPF updating. Raise and lower signals from the OPF software are in the one second range, and therefore OPF steady state power data need to be calculated in the order of one to a few seconds. At upper supervisory hierarchies, the calculation requirement can be even longer. The fast calculation lies mainly in dynamic system response enhancement: improvement of system damping, some forms of power conditioning, and more traditional analog controls. These fast controls can have calculation requirements in the range of a few cycles of a 60 Hz signal, or down to about one cycle (i.e., about 17 ms). Although electromechanical time constants and traditional PSS controls operate on a much longer time scale – up to a few seconds – there are distinct advantages that can be realized by implementing controls into the tens of milliseconds. These advantages are improvement of damping, and detection and correction of anomalous conditions.

The remarks above indicate that there is a need for the rapid determination of the mode of a FACTS controller. This is depicted in Figure 6-2.

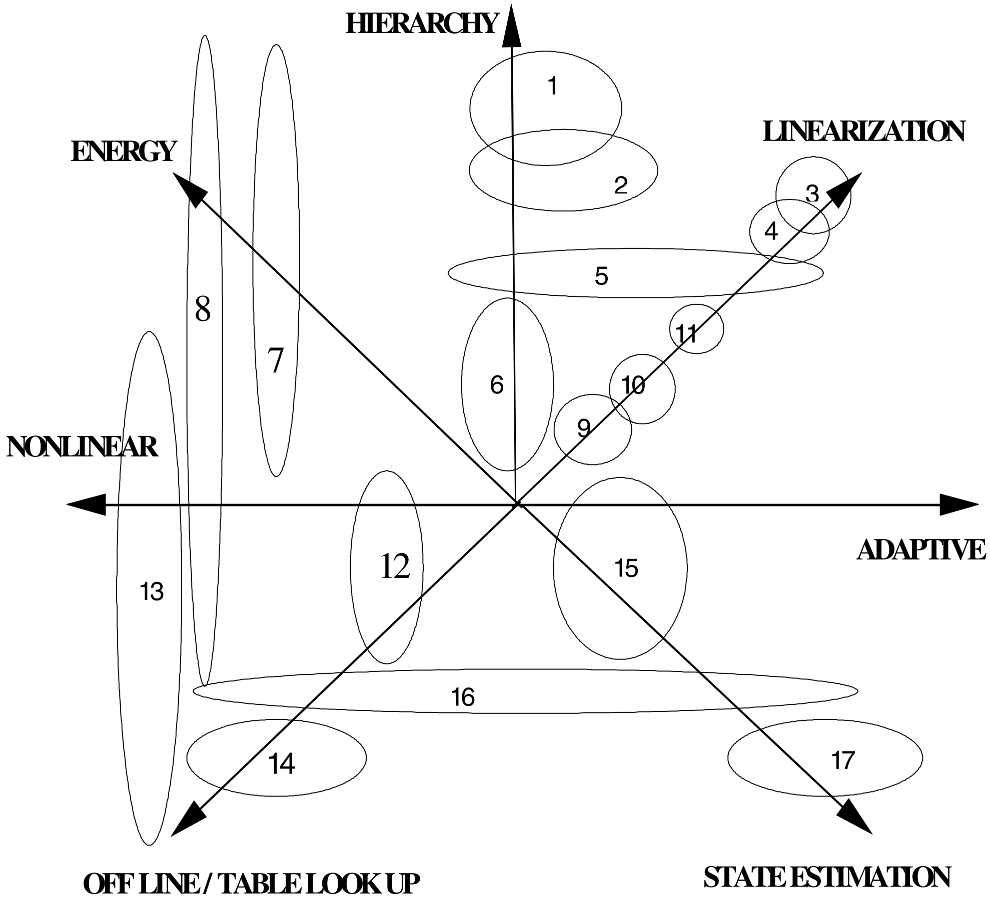
6.3 Steady State Operating Mode Algorithms

The general structure of the steady state operating mode is that of identification of the steady state, verification of the steady state, and execution of the selected control strategy. The latter can be based on the fast decoupled power flow study plus OPF considerations. In that case, signals must be received from the automatic generating control system to raise and lower generating levels, and accommodate the power flows appropriately. The alternative is to use a table look up / stored case solutions strategy. Figure 6-3 shows the general structure of the two steady state operating mode strategies.

Examples of selected methods of fast solutions for steady state control are shown in Appendix C.

Table 6-2
Fast analysis methods

Method	*Applicability*			*Basis*
	Steady state	*Tran-sient*	*Coordi nated*	
One iteration of a decoupled power flow study	X			Single iteration of an iterative method
Fast decoupled load flow study	X			Newton Raphson method, fast formulas for jacobian matrix
One iteration of a Gauss-Seidel power flow study	X			Single iteration of an iterative method
Power transfer distribution factors	X			Linearization / calculation of changed case
Line outage distribution factors, *N-1* contingency analysis	X			Linearization / calculation of changed case
Liapunov based methods, transient energy function		X		Calculation of total energy
Sensitivity of system eigenstructure		X		Linearization / calculation of changed case
Previous detailed solution updated by measurements or additional calculation	X	X	X	State estimation / weighted least squares / linearization
OPF modified by calculating pseudoinverse of coefficient matrix, and modification for a changed case	X			State estimation / weighted least squares / linearization
Supervisory control passes modification signal to lower hierarchical level when a changed case is sensed (i.e., adaptive hierarchical controller)	X	X	X	Adaptive control
Inverse control – assume solution, calculate control signal to produce the desired solution	X	X	X	State estimation / direct solution
Stored solutions – table lookup	X	X	X	Off-line calculation / table lookup
Pattern recognition	X	X	X	Off-line calculation / table lookup
Artificial neural network tuned with many known cases	X	X	X	Nonlinear estimator
Hierarchical control based on time hierarchy		X		Adaptive control
Hierarchical control based on objective hierarchy	X	X	X	Adaptive control
Hierarchical control based on linearity hierarchy or system impact hierarchy	X	X	X	Adaptive control



Legend

1	Time hierarchical control	9	Fast decoupled power flow
2	Objective hierarchical control	10	One iteration decoupled power flow
3	Line outage distribution factors	11	One iteration Gauss Seidel
4	Power transfer distribution factors	12	Artificial neural networks
5	Impact and linearity hierarchies	13	Pattern recognition
6	Adaptive hierarchical control	14	Table look-up
7	Eigenstructure sensitivity	15	Inverse control
8	Liapunov methods	16	Detailed solution + update
		17	OPF and modification of changed cases

Figure 6-1
Web diagram depicting the main rapid calculation methods for transient and sinusoidal steady state controls. The axes depict various control strategies, and the radial distance from the center roughly indicates the reliance on the cited strategy.

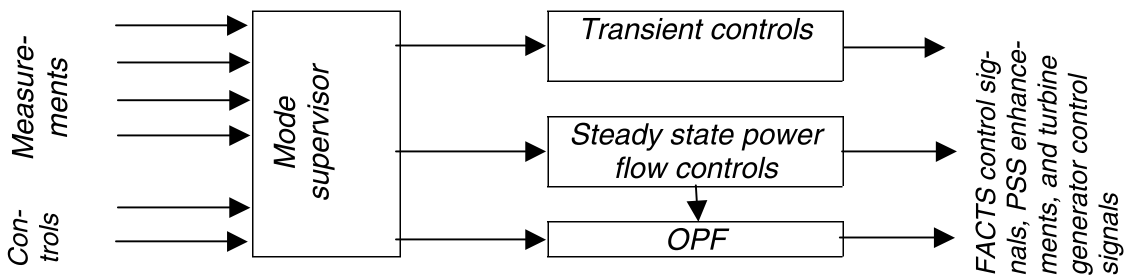


Figure 6-2
Calculation of the required FACTS controller mode

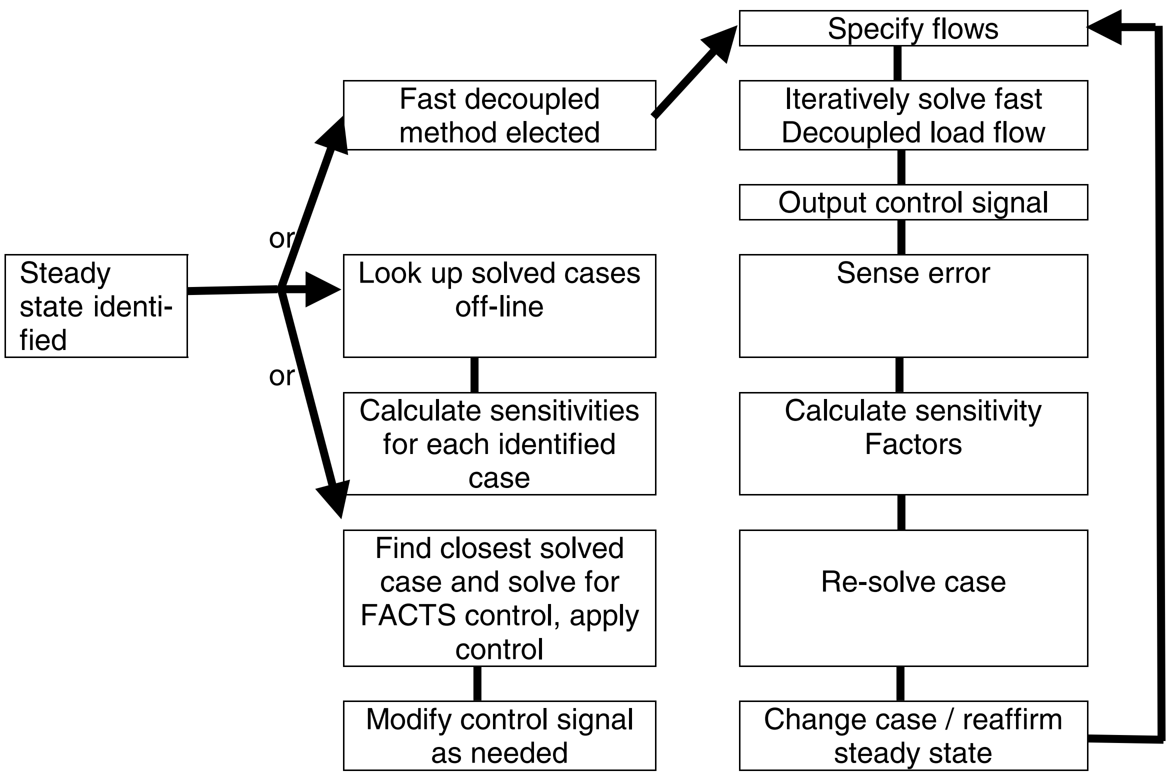


Figure 6-3
The steady state operating mode

6.4 Transient Operating Mode Algorithms

As indicated in the previous section, the identification of the steady state and transient mode must be done before taking control action. Thus identification must be verified and the process continues. If the transient mode is selected, the general control action is a calculation of the desired steady state solution, a calculation of the strategy to move in this direction, and a calculation of the FACTS control signals to accomplish this. The running process error is used in a feedback mode to regenerate the correct FACTS control signals. The general structure is shown in Figure 6-4.

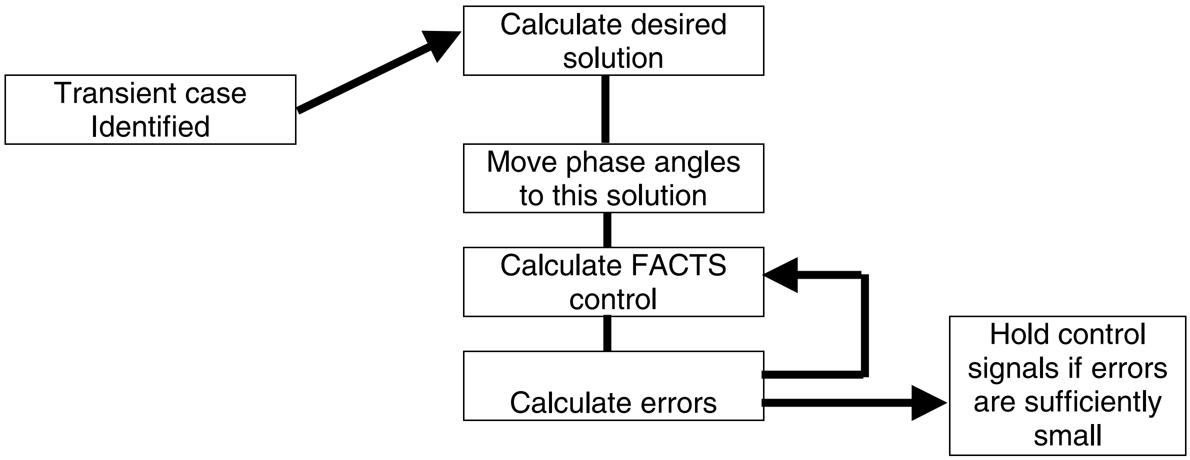


Figure 6-4
The transient state operating mode

6.5 Limitations of the Methods

The limitations of the methods described above are discussed in two sections: the first relating to the steady state controls, and the second relating to transient controls.

Steady state controls

The main formulation of fast steady state methods is based on Taylor series technologies. These methods rely on the calculation of the slope of trajectories that are linearized: that is, the system Jacobian matrix, J, is assumed constant for each iteration, and iterates are used to find desired controls. In the steady state, these controls are updated using measurements, and the result is a hopefully convergent series of controls, u, which approach u^* the optimal control to produce the desired effect (e.g., unloading a line, distributing the load in a transmission system, etc.).

The error resulting from the Taylor series truncation is dependant on the derivative of the Jacobian matrix with respect to the system controls, dJ/du. This derivative is a three dimensional array known as the Hessian tensor. If J is constant, the Hessian is zero, and the error is also zero. If the Jacobian entries are highly varying, Hessian entries may be large, and the error due to the truncation can be very large. The result is that the error in the control is dependent on two main factors,

- The magnitude of the Jacobian sensitivities with respect to the system controls (i.e., Hessian tensor values)
- The rate of system measurements to correct the controls.

The limitation of fast methods is based on the two cited factors. If the *dJ/du* terms are large, there may be unacceptable error in the control sequence *u(t).* If the rate of measurement processing is too slow, there may be an unacceptable error in the control sequence. The two factors have a compounding effect that is pictorially illustrated in Figure 6-5. A typical figure of one measurement per second is cited as a measurement rate, and a degrading of response time of 5 to 10 seconds for an applied FACTS control is estimated. This means that the methods are limited to load variations in the same range: 5 to 10 seconds.

The foregoing indicates that the main limitation of the fast methods is dependent on the measurement sampling rate and the power flow Jacobian matrix. Both effects are measurable as the mismatch expressions *ƛP, ƛQ.* This mismatch expression is a direct measure of the accuracy of the method, and this can be used to generate a confidence index.

Transient case

The transient control case and the limitations of the fast power flow methods (and other fast methods discussed in this chapter) is discussed here. In this case, the optimal FACTS control *u** is contaminated by an error *ƛu.* For the case of a linear system, the state vector that evolves from *u*(t),* and that that evolves from *ƛu(t)* can be superimposed to give the resultant system state. The nature of the error is depicted in Figure 6-6.

The limitation of the fast method in this case again depends on the sensitivity of the system state response to the control signal, and also the speed of the measurements (which are correcting the error). Probably, in most cases, the measurement rate is the limiting factor, and this is estimated for the case of one measurement per second as a degradation of response time by 4 to 5 seconds. If the state vector *X(t)* is changing slowly, this limitation is acceptable. If there are rapid system changes, this limitation is not acceptable, and the measurement sampling rate would have to be increased.

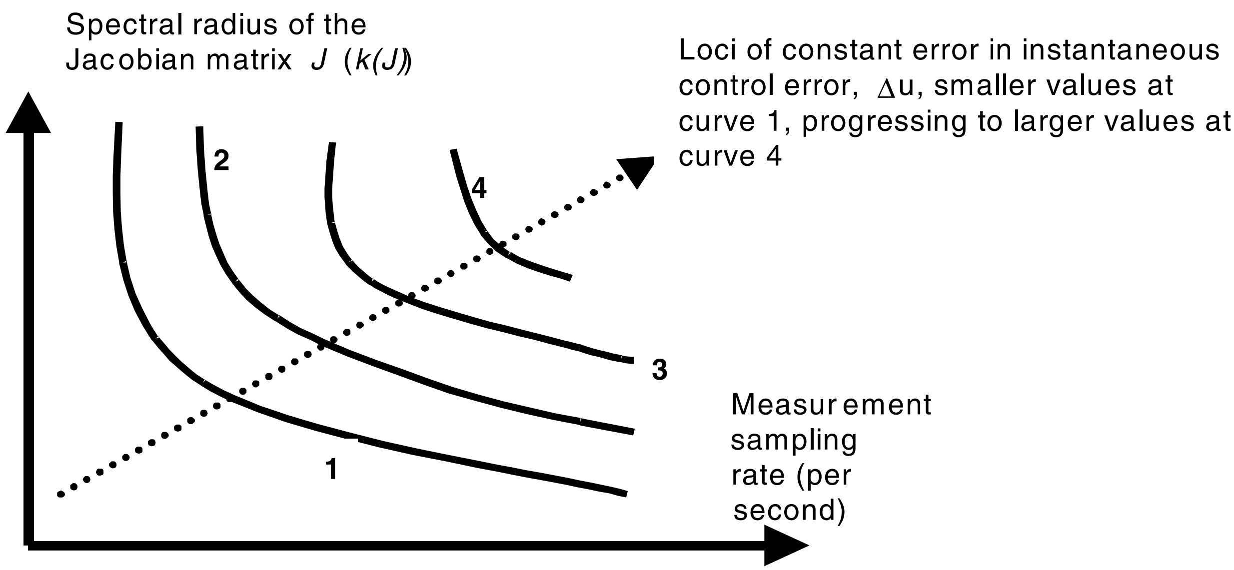


Figure 6-5
Pictorial of the interaction of measurement sampling rate and power flow Jacobian matrix spectral radius for FACTS controllers using fast power flow methods (steady state controls)

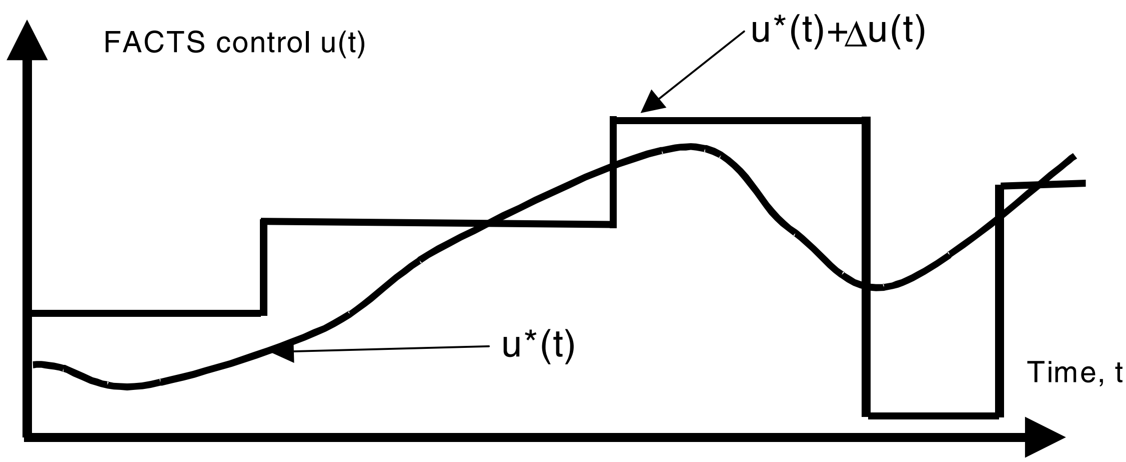


Figure 6-6
Depiction of error in the calculation of a FACTS control *u(t)*

6.6 Summary

Fast calculation methods have some promise in the implementation of FACTS controls. The main methods of interest are:

- One iteration of a decoupled power flow study
- Fast decoupled load flow study
- One iteration of a Gauss-Seidel power flow study
- Power transfer distribution factors
- Line outage distribution factors, *N-1* contingency analysis
- Liapunov based methods, transient energy function
- Sensitivity of system eigenstructure
- Previous detailed solution updated by measurements or additional calculation
- OPF modified by calculating pseudoinverse of coefficient matrix, and modification for a changed case
- Supervisory control passes modification signal to lower hierarchical level when a changed case is sensed (i.e., adaptive hierarchical controller)
- Inverse control – assume solution, calculate control signal to produce the desired solution
- Stored solutions – table lookup
- Pattern recognition
- Artificial neural network tuned with many known cases
- Hierarchical control based on time hierarchy
- Hierarchical control based on objective hierarchy
- Hierarchical control based on linearity hierarchy or system impact hierarchy.

For the case of steady state controls, the errors introduced by the fast approximations are not likely to degrade system response. The main factors in this consideration are:

- The magnitude of the Jacobian sensitivities with respect to the system controls
- The rate of system measurements to correct the controls.

For the transient case, these methods are less promising due to transient error which can slow response by as much as 5 seconds in typical applications. However, for slowly varying state dynamics, the methods appear suitable.

CHAPTER 7

COMPARISON OF ALTERNATIVE CONTROL METHODS AND APPLICATIONS

7.1 Comparison of Alternative Methods

In this chapter, a comparison of the alternative methods described in Chapters 3 – 6 is given. The focus of these comparisons is for applications to FACTS technologies. For quick comparison, the methods are tabularized and described in selected categories. The categories of comparison are:

- Technical bases of the methods
- Existing applications in power engineering and other areas of engineering
- Applicability to steady state control of FACTS controllers
- Applicability to transient control of FACTS controllers
- Speed of calculation requirements (on-line and off-line)
- Central processing unit (CPU) requirements (both on-line and off-line)
- Sensory requirements (in both real time and for archival data)
- Main strengths and potential strengths
- Main weaknesses and potential weaknesses
- Research and development needs in implementation.

The methods that are compared are numbered and denominated by the titles in *italics* for this comparison:

1. *Expert systems*
2. *Artificial neural networks*
3. *Fuzzy logic* controls
4. *Evolutionary algorithms*
5. *Genetic algorithms*
6. *Transportation methods*
7. One iteration of a *decoupled power flow* study

8. *Power transfer distribution factors*
9. *Line outage distribution factors*, *N-1* contingency analysis
10. *Liapunov* based *methods*, transient energy functions
11. *Sensitivity of system eigenstructure*
12. Previous detailed *solution updated* by measurements or additional calculation
13. *Inverse control* – assume solution, calculate control signal to produce the desired solution
14. *Stored solutions* – table lookup
15. *Pattern recognition*
16. *Hierarchical control* based on *time* hierarchy
17. *Hierarchical control* based on *objective* hierarchy.

7.2 Technical Bases of the Methods

Table 7-1 is a summary of the fundamental technical bases of the alternative methods listed in Section (7.1).

7.3 Existing Applications

Table 7-2 is a listing of existing applications of the methods listed in Section (7.1). Applications in power engineering as well as other branches of engineering are listed.

7.4 Speed of Calculation, Sensory, and CPU Requirements

Table 7-3 lists estimates of calculate speed requirements, sensory inputs (both real time and for archival data), and CPU requirements (on-line and off-line) for the methods listed in Section (7.1). The application in each case is the FACTS controls described in Chapters 3-5.

7.5 Applicability of Alternative Methods to FACTS Controllers, Strengths, and Weaknesses

Table of comparisons

Table 7-4 shows the identified strengths and weaknesses of the methods listed in Section (7.1). These remarks were summarized from the foregoing sections and comparisons.

Applicability to FACTS device controllers

Table 7-4 is a general comparison of the methods discussed in this report. The true comparison of alternative methods is highly dependent on specific applications. Specifically, the main elements that effect the comparison are:

- Control objectives
- Desired response speed
- System size
- Interconnection of power system with other power systems
- Desired accuracy
- Computer capabilities
- Implementation of the software
- Dynamic range that must be accommodated
- Availability of archival information and format of this information
- Type of FACTS controller(s).

In consideration of these issues, one comparative conclusion of this study is that the transportation method, either as described in Chapter 5 or augmented by a state estimation / sensory systems, is probably the most appropriate control logic for FACTS device control. The technology is broadly applicable in a wide range of areas in which transport of a commodity (energy, power are included) is needed. There is a potential of using generalized software modules in the FACTS application. The inclusion of state estimation technologies makes the integration of instrumentation / sensory information feasible. And this integration adds to the accuracy and effectiveness of the control. The inclusion of sensory information also allows for the control of the nonlinear power system in steps – adaptively modifying the control as needed as time progresses. The computational requirements of the transportation method are modest and actually rather low in the real time environment. This is because some computationally intensive operations are executed off-line. The tests, assessment, literature analysis, and experimentation indicate that the transportation method is to be recommended for FACTS device control logic.

Table 7-1
Comparison of technical bases of methods

Method		*Basis of the method*
1	Expert systems	Construct rule base like those used in actual operational practice by expert operators
2	Artificial neural networks	Adaptive tuning of a specialized configuration of nonlinear system
3	Fuzzy logic	Manipulation of signals and parameters whose values are represented by a range of values rather than fixed quantities
4	Evolutionary algorithms	Specialized ordering of a search of a solution space
5	Genetic algorithms	Specialized ordering of a search of a solution space
6	Transportation methods	Conservation of power end energy
7	Decoupled power flow	One iteration of the Newton Raphson power flow study, one term in a Taylor series expansion
8	Power transfer distribution factors	Differentiation and linearization
9	Line outage distribution factors	Differentiation and linearization
10	Liapunov methods	Calculation of total energy, and differentiation of this expression to obtain a measure of reduction of energy of a dynamic system
11	Sensitivity of eigenstructure	Properties of linear dynamic systems
12	Updated solutions	State estimation
13	Inverse control	State estimation, iterative solution, inverse system theory
14	Stored solutions	Pattern recognition, linearization, table lookup
15	Pattern recognition	Recognition of a previous seen dynamic response or steady state solution
16	Hierarchical control – time	Linear (or near linear) systems in specified time horizons
17	Hierarchical control - objective	Linear (or near linear) systems in specified operating states

Table 7-2
Existing engineering applications of the methods

Method		Application area	Applicability		
			Steady state	*Tran-sient*	*Coor-dinated*
1	Expert systems	General information processing, computer programming, information technology applications	X	X	X
2	Artificial neural networks	General control applications, identification applications	X	X	X
3	Fuzzy logic	General control applications	X	X	X
4	Evolutionary algorithms	Experimental	X	X	X
5	Genetic algorithms	Experimental	X	X	X
6	Transportation methods	Civil infrastructure applications (e.g., highways, natural gas, mass transit), power flow studies	X	X	X
7	Decoupled power flow	Power flow studies	X		
8	Power transfer distribution factors	Power flow studies	X		
9	Line outage distribution factors	Power flow studies	X		
10	Liapunov methods	General applications in dynamic studies, transient stability studies		X	
11	Sensitivity of eigenstructure	General applications in dynamic studies, transient stability studies		X	
12	Updated solutions	General control applications	X	X	X
13	Inverse control	General control applications	X	X	X
14	Stored solutions	Image processing, fingerprint identification, security systems	X	X	X
15	Pattern recognition	Widespread applications in information technology, digital signal processing, image processing	X	X	X
16	Hierarchical control – time	General control applications in large scale systems	X	X	X
17	Hierarchical control – objective	General control applications in large scale systems	X	X	X

Table 7-3
Sensory and processing requirements of the methods applied to FACTS controls (1)

	Method	*Processor speed requirements*		*CPU requirements*		*Sensory measurement requirements*	
		On-line	*Off-line*	*On-line*	*Off-line*	*Real time*	*Archival*
1	Expert systems	Modest / low	Modest / high	Modest	Very high / extremely high (2)	Modest	High / very high (2)
2	Artificial neural networks	Low	Modest	Low / very low	High / very high (2)	Modest	High / very high (2)
3	Fuzzy logic	Low	Modest	Low	Modest	Modest	Modest
4	Evolutionary algorithms	Low	High	Very low / low	High	Modest	Modest
5	Genetic algorithms	Low	High	Very low / low	High	Modest	Modest
6	Transportation methods	Low	Low / none	Modest	Low / none	High / very high	Low / none
7	Decoupled power flow	Low	Low / none	Modest	Low / none	Low / modest	Low
8	Power transfer distribution factors	Very low	Modest	Very low	Modest	Low	Low
9	Line outage distribution factors	Very low	Modest	Very low	Modest	Low	Low
10	Liapunov methods	Modest / high	Low / modest	Low	High	Low / none	Low / none
11	Sensitivity of eigenstructure	Modest / high	Low / modest	Low / medium	High	Low / none	Low / none
12	Updated solutions	Low	Low / medium	Low / medium	High	Medium / high	High / very high
13	Inverse control	High / very high	Low / none	Medium	Medium / low	Low / none	Medium / low or none
14	Stored solutions	Low / very low	Medium / low (2)	Medium / low	Very high / extremely high (2)	Low / none	Medium / low or none (2)
15	Pattern recognition	Low / very low	Medium / low (2)	Medium / low	Very high / extremely high (2)	Low / none	High / medium (2)
16	Hierarchical control – time	Modest	Modest	Medium	Medium / low	Low / none	Low
17	Hierarchical control – objective	Modest	Modest	Medium	Medium / low	Low / none	Low

(1) Obviously processing requirements vary in a highly complex manner with system size, operating point, control objective, proximity to nonlinearity, and other factors. The estimates in the table are for a large interconnected power system (e.g., 1000 – 5000 transmission buses) with control objectives of distributing the load in the transmission system.
(2) An extremely large number of off-line cases may need to be processed.

Table 7-4
Comparison of strengths and weaknesses of alternative methods

	Method	*Identified strengths*	*Identified weaknesses*
1	Expert systems	• Utilizes recognized rules of system behavior • Accommodates very complex system response	• Difficult to include physical model • Potentially will not accommodate cases and operating conditions never seen before
2	Artificial neural networks	• Transfers the bulk of calculations to off-line • Fast solution / simple model	• Potentially very large number of off-line cases to be solved • Does not utilize known physical model information well
3	Fuzzy logic	• Smooth control	• May have heuristic selection of parameters
4	Evolutionary algorithms	• Moves processing of data to off-line	• May not process data well for cases never seen before
5	Genetic algorithms	• Moves processing of data to off-line	• May not process data well for cases never seen before
6	Transportation methods	• Fast calculation due to minimal representation of system dynamics • Allows utilization of both model and sensory information in a state estimation formulation	• Does not represent losses well • Does not represent system dynamics well • May require large number of sensory inputs
7	Decoupled power flow	• Fast solution • Maximizes utilization of bus voltage amplitude and reactive power, and active power – phase angle relations • Easy to formulate control problem	• Accuracy in question • Requires sensory information to compensate for solution error
8	Power transfer distribution factors	• Fast solution • Can be used to analyze many changed loading cases quickly	• Accuracy in question • Difficult to estimate error • Requires sensory information to compensate for solution error
9	Line outage distribution factors	• Fast solution • Can be used to analyze many line outage cases quickly	• Accuracy in question • Requires sensory information to compensate for solution error
10	Liapunov methods	• Rapid calculation of stability • Linearized control theory applicable	• Difficult to represent functional form of energy content of a system • Conservative results
11	Sensitivity of eigenstructure	• Fast solution • Linearized control theory applicable	• Linearized solution, may contain errors for a nonlinear system • Difficult to assess accuracy
12	Updated solutions	• Transfers the bulk of calculations to off-line	• Potentially very large number of off-line cases to be solved • Does not utilize known model information well
13	Inverse control	• Seemingly a direct path to a desired target solution	• Solution is in reverse time and difficult to accommodate sensory information in real time
14	Stored solutions	• Transfers the bulk of calculations to off-line • Fast calculation (identification) of control	• Can not accommodate unknown cases (i.e., cases not seen before) • Many cases must be processed off-line / many cases to scan through • Difficult to assess whether all operating cases have been seen
15	Pattern recognition	• Very rapid on-line processing • Allows real time dynamic control	• May not recognize operating conditions that have never been 'seen' before
16	Hierarchical control – time	• Does detailed calculation in specified narrow time windows	• Time windows need to be changed as solution progresses, difficult to devise smooth transition
17	Hierarchical control – objective	• Detailed solution at given levels of the control structure	• Difficult to devise smooth transition between hierarchical levels

CHAPTER 8

CONCLUSIONS AND IDENTIFIED RESEARCH NEEDS

8.1 Conclusions

The main conclusions of this research are:

FACTS controllers are useful for both steady state and dynamic controls in power systems. Also, the control speed capability of FACTS controllers exceeds the requirements of both dynamic and steady state power system controls.

FACTS controllers offer the possibility of transmission congestion alleviation and ATC improvement.

FACTS controllers may be used to improve system dynamic response, power flow control and management.

The transportation method offers a useful method to effectuate FACTS control objectives.

System sensory measurements should be used to improve the accuracy of the calculation of FACTS control signals. These signals should be imported to a FACTS control calculation in a way similar to weighted state estimation calculations.

Intelligent methods and genetic algorithms may be used to determine the secure operating states of a power system, and these may be used to determine the ATC constrained to those secure operating conditions.

FACTS controllers offer an alternative to special protection schemes. This alternative has the advantage of not requiring generation to be taken off line.

8.2 Research and Development Needs

General recommendations

The main research and development needs and recommendations for control logic strategies for FACTS controllers are listed in this section.

A key research and development need is to convert the transportation method to a simulation tested control logic for FACTS controllers. This entails reformulation of the power flow study problem to include transportation models of FACTS controlled systems. Sensory measurements should be included in the model. Sensor weights should be studied and selected to optimize performance.

A second key research need is the incorporation of FACTS controls into optimal power flow methods. This area too involves the inclusion of weighted sensory measurements.

A third development need is the construction and testing of practical FACTS control software for application to an existing system.

These needs are identified with the following concomitant research needs:

- To identify a specific FACTS controller to be used in transmission congestion alleviation, and to simulate a range of study cases to demonstrate the effectiveness of the device under historically measured conditions.

- To formulate an accurate model of the selected FACTS controller based on the power electronic implementation of the device, including nonlinearities, dynamic range, and device dynamics where appropriate.

- To expand the transportation technologies outlined in this report and to accommodate the types of control signals and control capabilities of the identified FACTS controller.

- To construct the transportation method utilizing actual power system data, and evaluate the confidence index (residual) for historical data. This includes a full chi-squared confidence evaluation of the residual, and the calculation of the percent confidence to attain a given level of residual.

- To test alternatives in selection of the weighting matrix for sensory measurements.

- To formulate a reliable mode selection algorithm for the setting of the FACTS controls to steady state or dynamic control modes.

- To evaluate alternative sparcity coding methods for implementing the transportation method for large systems.

- To integrate sensory information into the control method utilizing actual data, and to test conditions of missing or bad data

- To evaluate the technique of weight selection for sensory signal integration.

Specific recommendation for research and development

The pilot study described in this report describes the basis of FACTS control logic. The purpose of the pilot project was to develop control logic concepts to enhance the functionality of FACTS controllers in transmission systems. The subsequent phase of this work should be to *implement* innovative control logic strategies in an Energy Management System with the objectives of increasing power transfer capability, stability, and reliability through effective control and dispatch. Applications in remedial controls need to be studied further and implemented.

The key research needs identified should be coordinated with a host utility company. Large scale implementation of the selected control logic strategies should be performed. It is important to construct the mode selection scheme to be used: FACTS controllers should be used for a variety of tasks, and the objectives of the tasks shall be selected in a mode selection process. This is at the core of the control logic design. *The main portion of the identified research needs is the incorporation of Available Transfer Capability optimization into the optimal power flow algorithms.* This is done to reduce transmission congestion in an optimal way. The strategy to be used is multi-objective optimization and injection control algorithms for power systems. As identified in this pilot study, transportation methods for controller design are appropriate as they are fast, they utilize measurements, and they iterate on the solution in real time as the control signals are calculated. The optimization is considered to be multi-objective because there are many ATC paths and these need to be weighted / prioritized. Also, the control logic will impact the system dynamic response as well as the production cost. These factors are included in the constrained optimization.

The most important part of the identified research and development needs is the development of the final control algorithm and the reduction of the theory to software. This should be done with a large scale system with focus on the host utility system. Upon construction of the software, a full evaluation of the code should be done with the host utility. Part of the identified needs is the evaluation of the ATC improvement afforded by the controller.

Specific recommendations for further work include the following:

- *Identification of the types of FACTS devices to be incorporated and develop the software models*

The types and analytical models of FACTS devices to be incorporated in the practical software should be determined in consultation with engineers from host EPRI member companies.

- *Development of practical algorithms for optimal dispatch of the Available Transfer Capabilities in interconnected power systems and remedial control*

It has been shown that FACTS controls can expand the Total Transfer Capabilities and reduce the Transmission Reliability Margin. The control logic is based on optimization methods and transportation congestion management techniques. Remedial controls using FACTS devices have also been demonstrated. Actual power system models should be developed for use with practical control logic algorithms. This involves detailed modeling of the power system and the set of identified FACTS controllers to be used. The optimization algorithms need to be tested. The concept of Pareto-optimal solutions is important here. Given that there are multiple paths for which the ATC will be dispatched, it is necessary to determine the Pareto-optimal solutions and perform tradeoff among these solutions. Considerations for the tradeoff include systems security and economics. Genetic algorithms can serve as a search engine for the Pareto-optimal solutions and a full investigation of this tool is recommended.

System dynamics need to be considered in the ATC calculation. The dynamic security criteria used by the host EPRI member company needs to be identified and reduced to a mathematical specification. The dynamic security criteria should be integrated into the ATC calculation algorithms.

In the pilot phase of this work, a relationship was identified between FACTS controllers and Special Protection Systems as *remedial controls*. If the FACTS controllers can be used effectively as remedial controls, they will be attractive tools to help avoid overloading and the associated problems that may arise. It is recommended to develop optimization algorithms that calculate the FACTS control configuration and settings for the purpose of remedial control. It will be desirable if the same computational techniques that allow the calculation of the optimal ATC dispatch will also be used for optimization of remedial controls.

- *Software implementation of the optimal ATC dispatch algorithms*

The coding of the control algorithms as efficient software is recommended. The software tools should be selected in consultation with EPRI and the host member companies. The goal is to select tools so that the developed package will be more efficient, generic and portable.

- *Validation and verification of the ATC dispatch software*

The control algorithms should be validated based on the specifications and test cases. Comments from EPRI and host companies should be requested and used for enhancement of the software. Test cases that are generic and representative should be selected so that the robustness of the algorithm can be achieved.

- *Development of implementation plans for the ATC dispatch algorithms in a practical environment*

The proposed Pareto-optimal ATC dispatch algorithm is a new tool for the power market environment. The implementation of the tool requires a thorough analysis. Considerations include the software and hardware environment, data requirements, data acquisition associated with the new tool, and market data for economic evaluation. Researchers should work with the host companies to develop implementation plans for the new ATC dispatch software.

- *Computer demonstration of the optimal ATC dispatch algorithms*

Computer demonstrations should be done for EPRI and the host companies.

APPENDIX A

REVIEW OF THE LEAST SQUARES SOLUTION OF *Ax = b* AND APPLICATIONS TO TRANSPORTATION SOLUTIONS

A.1 Theoretical Background

The linear state estimation problem is discussed in considerable detail elsewhere (e.g., [J2]); however, a very brief review is given here with an emphasis on the application to the control of FACTS devices. The basic equation

$$Ax = b \tag{A.1}$$

with A having dimension N_r by N_c, x is a vector of dimension N_c, and b a vector of dimension N_r, normally has the following solution structure:

when $N_r > N_c$	There are more equations than unknown and in general there are no authentic solutions
when $N_r = N_c$	There may be one single solution, and infinite number of solutions, or no solutions depending on the eigenstructure of A
when $N_r > N_c$	There are more unknowns than equations, and there are an infinite number of solutions in general.

The first case is known as the overdetermined case; the second is the critically determined case; and the third is the underdetermined case. If one abandons the usual concept of a solution, namely that all rows of Equation (A.1) are satisfied, then one can 'solve' (A.1) in the least squares sense. That is, let

$$J = (Ax-b)^t(Ax-b). \tag{A.2}$$

Then J is called a residual and represents the degree to which the equations are 'solved'. That is, if J is zero, the equations are all solved in the usual sense. If J is small, then Equation (A.1) nearly is correct, and the value of x at this 'solution' is an estimate. When x is estimated in this way, it can be simply shown that the squared error in each equation of (A.1) is minimized (i.e., the sum is minimized), and the value of x is called the least squares solution. Because each equation in (A.1) is weighted evenly, the estimate x is called the unbiased estimate.

It is a simple matter to obtain the biased estimate as follows: let

$$J = (Ax-b)^t W(Ax-b). \tag{A.3}$$

where W is a N_r by N_r matrix. Matrix W is called a weight matrix and it is, in effect, the weighting of the validity of the N_r different rows of Equation (A.1). The minimization of Equation (A.3) is called the weighted least squares problem – or the biased estimate. For $W = I$ = the identity matrix, the weighted case becomes the unbiased case.

The calculation of vector x to minimize J has been done in many places (e.g., [J1], [J3]). This is the linear state estimation problem, and the solution is written as $\overline{x}$; it can be shown that $\overline{x}$ for the unbiased case is

$$\overline{x} = (A)^+ b. \tag{A.4}$$

and for the biased or weighted case is

$$\overline{x} = (\sqrt{W}A)^+ \sqrt{W}b. \tag{A.5}$$

The notation $(\cdot)^*$ refers to the pseudoinverse, and Table A-1 shows ways to calculate this matrix.

Table A-1
The pseudoinverse of matrix *A*

Case	*Pseudoinverse, A^+*
Overdetermined	$(A^tA)^{-1}A^t$
Critically determined	A^{-1}
Underdetermined	$A^t(AA^t)^{-1}$
General case	$E\Sigma^{-1}F$ where E and F are modal matrices of the left and right singular vectors of matrix H and Σ is a diagonal matrix of the nonzero singular values of H. [J1]

A.2 Accuracy of Transportation Solutions

The accuracy of transportation solutions is the same as the accuracy of the biased state estimation problem. The main element that is a discriminator between accurate and inaccurate solutions is the value of the residual *J*,

$$J = (Ax-b)^t W(Ax-b).$$

If the residual is zero, the solution is perfect – for the stated model. If the residual is large, the accuracy is poor. The question of large relative to what is raised: the root mean square error is simply

$$rms\ error = \sqrt{\frac{J}{N}}$$

Where N is the number of equations in the state estimator (i.e., the row dimension of vector b). It is assumed that the error should not include influence from the bias weights, and therefore the determinant of W is assumed to be unity. If this is not the case, the residual can be scaled by $det(W)$.

It is possible to estimate the confidence in the solution if the statistics of the measurement noise and other errors in the state space model are known. Also, this problem is only simply calculable for the case of assumed gaussian measurement noise. In such a case, the residual is chi-square distributed because ($Ax-b$) is gaussianly distributed. The quadratic form of a gaussian process is chi-square distributed. There are tables of chi-square confidence versus assumed values of the variance of the measurement noise and required probability of error. Reference [J2] has such a procedure outlined.

The application of the chi-square test to FACTS controllers could be done in order to alert the controller of the potential of error in the control. For example, the following measures could be taken to implement a control error mitigation strategy:

- If the chi-square test gives a poor confidence value, controls are slowed. This is done in order to allow the adaptive nature of the controller to catch up with the process dynamics. This can be accomplished by setting the control cycle to one per second when the confidence is 90% or greater; one per 10 seconds when the confidence is between 0.7 and 0.9; one per 30 seconds when the confidence is between 0.5 and 0.7; and one per 100 seconds when the confidence is below 0.5

- If the chi-square test gives a sufficiently poor confidence, an alarm can be issued to recommend manual control or some other special action.

- If the chi-square test gives sufficiently poor confidence, the operator may be asked to check manual readings / measurements.

The main issues in transportation solution accuracy are measurement error, the degrees of freedom, the singular spectrum of the state estimation matrix (especially the ratio of the largest to smallest singular value, also known as the condition number), and the validity of the linearization.

A.3 Example of Steady State Solution Using Transportation Methods

An example is presented to outline the transportation method of power system solution for a FACTS device control in the sinusoidal steady state. Figure A-1 shows the example system, and Table A-2 shows a 'Case A' loading. In the base case, the FACTS controller in Line 4 – 2 is set to –0.23 per unit active power flowing from 4 to 2 metered at 4. The example given is to study the base case power flow study shown in Table A-3, and calculate the FACTS device control signal to force the loading in Line 4 – 5 to +0.8 per unit active power (flowing 4 to 5 metered at 4). This represents a complete reversal and change of loading of the flow in Line 4 – 5 from the 'base case'.

The example is solved using Equation (5.9),

$$\begin{bmatrix} C \\ F \\ H \end{bmatrix} = \left[\sqrt{W} \begin{bmatrix} 0 & -L_{AF} & -L_{AH} \\ 0 & -L_{BF} & -L_{BH} \\ 1 & -L_{CF} & -L_{CH} \end{bmatrix} \right]^{+} \sqrt{W} \begin{bmatrix} -M_A + L_{AE}D_E + L_{AG}M_G \\ -M_B + L_{BE}D_E + L_{BG}M_G \\ L_{CE}D_E + L_{CG}M_G \end{bmatrix}. \tag{5.9}$$

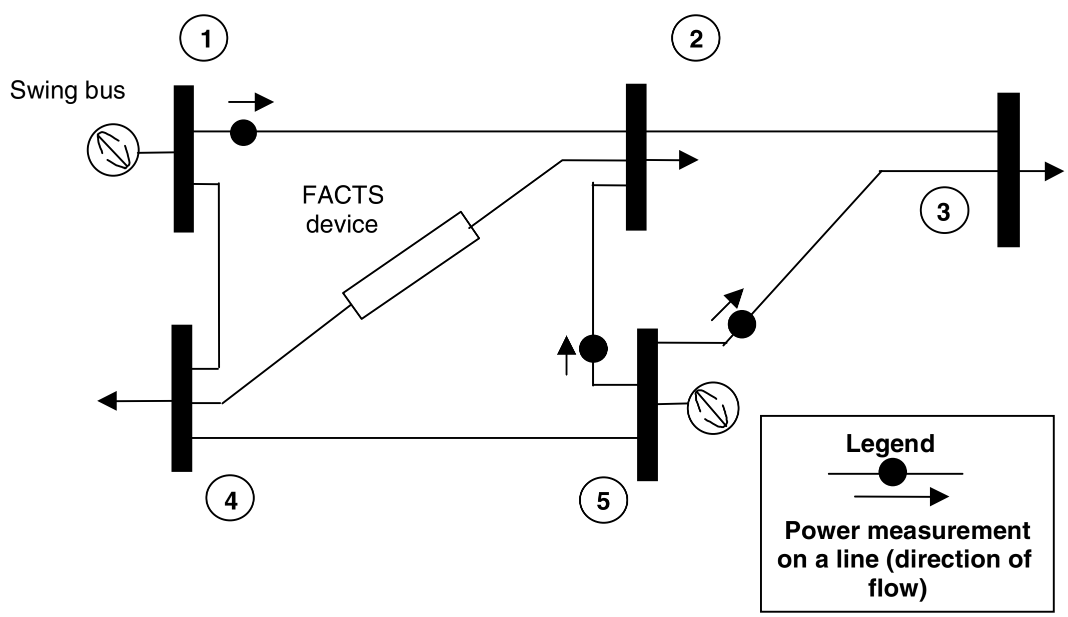


Figure A-1
Example system to illustrate the transportation power flow study method

Table A-2
Example system loads and line data 'Case A'

Line impedances	
Line	Impedance (p.u.)
1 – 2	*j0.01*
2 – 3	*j0.01*
1 – 4	*j0.01*
4 – 5	*j0.01*
5 – 2	*j0.01*
5 – 3	*j0.01*

Bus loads / generation		
Bus	Active load power (p.u.)	Generation (p.u.)
1	Swing bus	
2	2.0	
3	1.0	
4	3.0	
5		3.0

Table A-3
Load flow study of the example system in 'Case A'
(all values in per unit, "Case A' loading, swing bus at rating)

Bus voltages	
Bus	Voltage (p.u., degrees)
1	1.00 ⊃ 0.000 ^{o}
2	1.00⊃-0.791 ^{o}
3	1.00⊃-0.831 ^{o}
4	1.00⊃ -0.923 ^{o}
5	1.00⊃-0.269 ^{o}

Line flows	
Line	Active power flow
1 – 2	1.38
2 – 3	0.07
1 – 4	1.61
4 – 5	-1.14
5 – 2	0.91
5 – 3	0.98
4 – 2 *	-0.23

*Line 4 –2 is a FACTS controlled line set to –0.23 per unit active power flow in the base case

In this case, the unbiased solution is used, $W = I$. In the changed case, the measurement vector MG will change to $(3, 2.3, 1.6)^T$ and the desired line setting in Line 4 – 2 will be (+0.8). For reference, the various subvectors and submatrices are,

$A = null$
$M_B = (2,1,3,-3)^T$
$L_{BE} = (0,0,1,-1)$

$$L_{BH} = \begin{bmatrix} 1 & 0 \\ -1 & 0 \\ 0 & -1 \\ 0 & 0 \end{bmatrix}$$

$L_{CF} = [0]$
$M_G = (3, 2.3, 1.6)^T$
$L_{CE} = 0$

$$L_{BG} = \begin{bmatrix} -1 & -1 & 0 \\ 0 & 0 & -1 \\ 0 & 0 & 0 \\ 0 & 1 & 1 \end{bmatrix}$$

$D_E = 0.8$
$L_{CG} = (1,0,0)$
$L_{BF} = (-1,0,1,0)$
$L_{CH} = [0, 1]$

The matrix and vector dimensions are

A	Null		M_A	Null		M_G	3 by 1
B	4 by 1		M_B	4 by 1		L_{BF}	4 by 1
C	Scalar		G	3 by 1		L_{CG}	1 by 3
E	Scalar		L_{BG}	4 by 3		L_{CH}	1 by 2
D_E	Scalar		L_{CE}	Scalar		L_{BE}	4 by 1
F	Scalar		L_{CF}	Scalar		L_{AE}	Null
W	5 by 5		H	2 by 1		L_{AG}	Null

The solution is found using the Matlab expressions

```
right=[-mb+lbe*de+lbg*mg; lce*de+lcg*mg];
zz=[0;0;0;0];
coeff=[zz,-lbf,-lbh; 1, -lcf, -lch];
cfh=Pinv(coeff)*right;
c=cfh(1)
f=cfh(2)
h=cfh(3:4)
```

and the solution is,

$C = [3.00]$ $\qquad$ $F = [-3.90]$ $\qquad$ $H = [-0.60, -0.10]^T$

Thus the FACTS control is –3.90 per unit power. When this is applied to the system, the result shown in Figure A-2 is obtained. Note the flow in Line 4 – 5 which was to be set to +0.8 per unit (a reversal of the original base case flow of –1.14 per unit). To clarify the example,

- Only active powers are illustrated (for simplicity, these are easily included in the subvectors)
- A single FACTS controller is illustrated here (the dimension of E is unity, and this is a program variable)
- No line charging or reactive power flows are included
- No ground ties are included
- No bus injections are forced to a particular set value; that is, subvector A is null. This is a program variable and would account for forced sales or purchase of power from adjacent systems
- Bus 1 is the swing bus and this is held to rated voltage and used as a reference phasor
- The bus voltages in the changed case are listed in Table A-4
- In the example above, the residual error is $J = 0.01$ per unit, which represents an rms error of 0.045 per unit
- There is one degree of freedom in this example (i.e., *equations* – *unknowns* = 1).

The general flow chart for the steady state algorithm appears in Section A.5

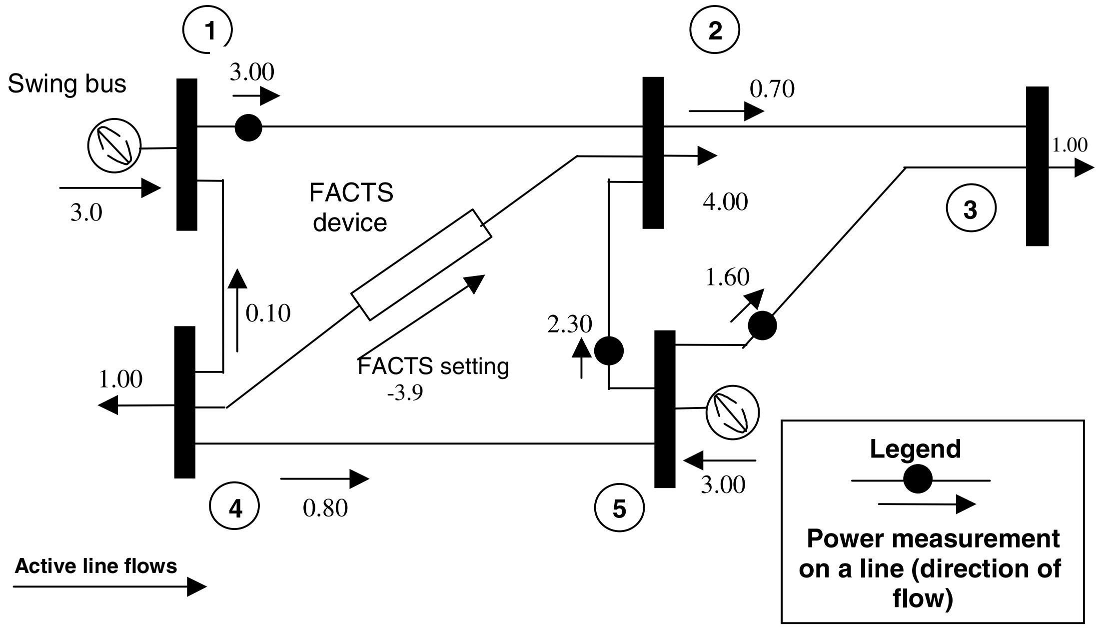


Figure A-2
System power flows in a small example, after a FACTS control is applied

Table A-4
Small example: bus voltages in FACTS controlled case (after application of FACTS control)

Bus	*Voltage (p.u., degrees)*
1*	1.00⊃ 0.0 °
2	1.00⊃-1.5 °
3	1.00⊃-1.1 °
4	1.00⊃ 0.1 °
5	1.00⊃-0.4 °

*Swing bus

A.4 Example of Transient Controls Using Transportation Formulation

In this section, the transient control of FACTS controllers using the transportation algorithm is illustrated. The simple mechanism described in the man text for power flow,

$$P_{ab} = \frac{|V_a||V_b|\sin(\delta)}{x}$$

is used, and Figure A-3 is repeated for convenience. The objective is to improve the eigenstructure of a dynamic system through the use if FACTS controllers: namely the movement of eigenvalues of the linearized system dynamics (at the point of operation) to the left in the complex plane. This corresponds to additional damping.

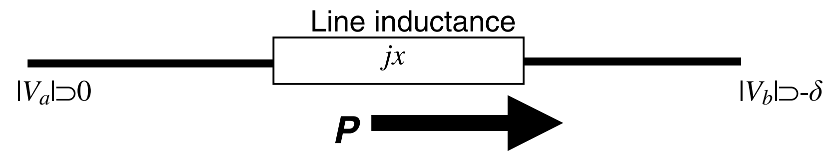


Figure A-3
Power flow in an inductive reactance *jx*

For purposed of the illustration of the method, the system of Figure A-4 is used. This system is very simple, but it allows a detailed examination of the system dynamics and coding of the implementation of the required FACTS controller. For the example, subscripts 1 and 2 refer to the generation buses 1 and 2, and bus x refers to the load bus at which a load of P_L occurs. Table A-5 summarizes the cases considered. These cases are discussed in detail below. For purposes of the examples, the line reactances are expressed in per unit as

$$jx_{1x} = j1/100$$

$$jx_{2x} = j1/50$$

and the generator terminal voltages are assumed to be fixed at rating.

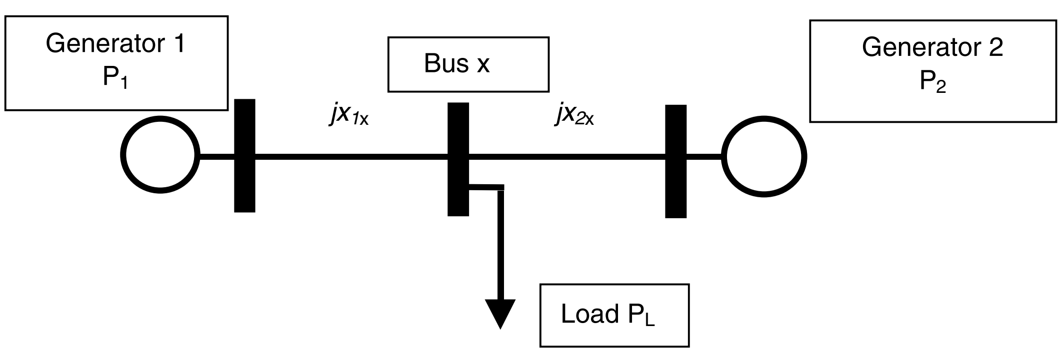


Figure A-4
Simple system for the illustration of added damping using FACTS controls

Table A-5
Example cases for the dynamic control of FACTS controllers using the transportation method

Example	*Purpose*	*Initial condition*	*FACTS Device*	*Load P_L (per unit)*	*Result (per unit values, degrees)*	*Observations / comments*
A-1	Base case	Loading profile is fixed $P_1 = P_2 = 0.5$ per unit	None	Fixed at 1.0	$\delta_1 = 0.00$ $\delta_2 = 0.2865$ $\delta_x = -0.2865$ $\lvert V_1 \rvert = 1.00$ $\lvert V_2 \rvert = 1.00$ $\lvert V_x \rvert = 1.00$	Base case
A-2	To show dynamics of system without FACTS controller, no damping present	$P_1 = 0.5$ and $P_2 = 0.5$ from $t = 0$ to $t = 3/60$ second. In this period, $P_L = 1.0$ Then load changes to 1.1 per unit with no change of generation. Generation changes to 0.6, 0.5 at $t = 6/60$ second.	None	Load fixed at 1.0 for t in the period [0, 3/60] second, then load increased to 1.1 per unit at $t = 3/60$ s.	Oscillatory case, solution using Matlab shows repeated zero eigenvalues, and one complex conjugate pair at $\lambda = \pm j4.714$	Dynamic case, no damping
A-3	To show dynamics of system *with* FACTS controller, damping introduced	As in A-2	Inserted in line *1 - X*	Load fixed at 1.0 for t in the period [0, 3/60] second, then load increased to 1.1 per unit at $t = 3/60$ s.	Depends on control used. See example below.	FACTS controllers can be used to introduce damping using transportation methods

Example A-1 Base case

The base case is a simple solution of the static expressions

$$P_1 = \frac{|V_1||V_x| \sin(\delta_x - \delta_x)}{x_{1x}} = \frac{1}{2}$$

$$P_2 = \frac{|V_2||V_x|\sin(\delta_2 - \delta_x)}{x_{2x}} = \frac{1}{2}.$$

For the case that δ_1= 0 (i.e., bus 1 is the reference phasor), the Matlab code for the solution (in degrees) is

```
dx=-asin(x1x*0.5);
d2=dx+asin(x2x*0.5);
ddx=dx*180/pi;
dd2=d2*180/pi;
ddx
dd2
```

and the solution is (degrees)

```
ddx =  -0.2865
dd2 =  0.2865
```

Example A-2 Dynamic case – no FACTS control

In this example, the system is solved without FACTS controllers. The conditions of the test are shown in Table A-5. The system equations are

$$P_1 = 100*\sin(\delta_1 - \delta_y)$$
$$P_2 = 50*\sin(\delta_2 - \delta_y)$$
$$\frac{1}{2} - P_2 = 3\frac{d^2\delta_2}{dt^2}$$
$$\frac{1}{2} - P_1 = 3\frac{d^2\delta_1}{dt^2}$$
$$P_1 + P_2 = 1$$

and the following definitions of state variables is made,

$Q_1 = \delta_1$	$Q_2 = d\delta_1/dt$	$Q_3 = \delta_2$	$Q_4 = d\delta_2/dt$
$Q_5 = P_1$	$Q_6 = P_2$	$Q_7 = \delta x$	$Q_8 = \delta y$

In this case, the variable δ_y is simply δ_x, that is the phase angle at the load bus. In Example A-3, a FACTS controller will be used to control δ_y separately from δ_x.

Because of the inclusion of the algebraic constraints (e.g., $\delta_x = \delta_y$), the lower order system becomes an eighth order system for this solution. This introduces one zero eigenvalue for each algebraic equation included in this way. Thus, the forth order system becomes an eighth order system in this case with four added zero eigenvalues.

A Matlab code is used to find the eigenvalues of the linearized system:

```
%initial condition
q0=[0;0;1/200;0;1/2;1/2;-1/200;-1/200];
%system matrices
a=diag(ones(8,1));
a(5,8)=100*cos(q0(1)-q0(8));
a(6,7)=50*cos(q0(3)-q0(7));
a(7,8)=-1;
a(8,5)=1;
a(8,6)=1;
a(8,8)=0;
b=[0,1,0,0,0,0,0,0;...
   0,0,0,0,-1/3,0,0,0;...
   0,0,0,1,0,0,0,0;...
   0,0,0,0,0,-1/3,0,0;...
   0,100*cos(q0(1)-q0(8)),0,0,0,0,0,0;...
   0,0,0,50*cos(q0(3)-q0(7)),0,0,0,0;...
   0,0,0,0,0,0,0,0;...
   0,0,0,0,0,0,0,0];
%calculation of eigenvalues of linearized system
eig(inv(a)*b)
```

And the system eigenvalues are found to be ! j4.714, 0, 0, 0, 0, 0, 0. The repeated zero eigenvalues are artifacts of the solution method which incorporates algebraic equation constraints in the form of derivatives: that is, the constraint $M = 0$ is written as $(dM/dt)=0$ so that the eigenstructure of the combined system is easily found.

It is concluded that this system is oscillatory with no damping, and natural frequency of oscillation 4.714 r/s.

Example A-3 Dynamic case – with FACTS control

In this example, the previous example is repeated with FACTS control inserted in line *x-1*. The concept illustrated utilizes a controller such as a UPFC capable of line power flow control. This is shown in Figure A-5. The solution is done as in the previous case; however a control equation is added,

$$P_1 = 100 * \sin(\delta_1 - \delta_y)$$

$$P_2 = 50 * \sin(\delta_2 - \delta_y)$$

$$\frac{1}{2} - P_2 = 3\frac{d^2\delta_2}{dt^2}$$

$$\frac{1}{2} - P_1 = 3\frac{d^2\delta_1}{dt^2}$$

$$P_1 + P_2 = 1$$

$$\delta_x - \delta_y = AP_1 + BP_2 + C(load) + D(\frac{d^2\delta_1}{dt^2}) + E(\frac{d^2\delta_2}{dt^2})$$

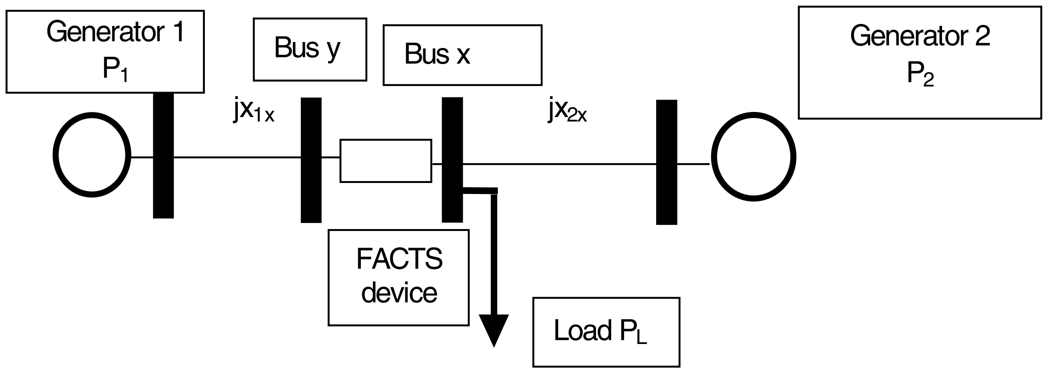


Figure A-5
Example system with FACTS control inserted

The form of the control shown here (i.e., the final equation) is shown as an illustration only. Other forms of controls can be incorporated in the same way. The state variables are,

$Q_1 = \delta_1$	$Q_2 = d\delta_1/dt$	$Q_3 = \delta_2$	$Q_4 = d\delta_2/dt$
$Q_5 = P_1$	$Q_6 = P_2$	$Q_7 = \delta_x$	$Q_8 = \delta_y$

And the Matlab coded solution for $A = 0, B = 0, C = 0, D = 2, E = -1$ is,

```
%initial condition
q0=[0;0;1/200;0;1/2;1/2;-1/200;-1/200];
%controls
d=2;
e=-1;
%system matrices
a=diag(ones(8,1));
a(5,8)=100*cos(q0(1)-q0(8));
a(6,7)=50*cos(q0(3)-q0(7));
a(7,8)=-1;
a(8,5)=1;
a(8,6)=1;
a(8,8)=0;
b=[0,1,0,0,0,0,0,0;...
   0,0,0,0,-1/3,0,0,0;...
   0,0,0,1,0,0,0,0;...
   0,0,0,0,0,-1/3,0,0;...
   0,100*cos(q0(1)-q0(8)),0,0,0,0,0,0;...
   0,0,0,50*cos(q0(3)-q0(7)),0,0,0,0;...
```

```
   0,0,0,0,-d/3,-e/3,0,0;...
   0,0,0,0,0,0,0,0];
%calculation of eigenvalues of linearized
%system
eig(inv(a)*b)
```

The eigenvalues are found for this case to be –32.65, -0.681, 0, 0, 0, 0, 0, 0. The repeated zero eigenvalue is due to the way the problem was solved – namely by converting the algebraic expressions to differential equations for ease in solution. A more complete study for this particular illustration reveals the result in Figure A-6 showing that the FACTS controller can introduce damping on the basis of a linearized transportation model. For the result depicted in Figure A-6, only control variables *D* and *E* were varied – similar results are obtained by varying *A, B, C.*

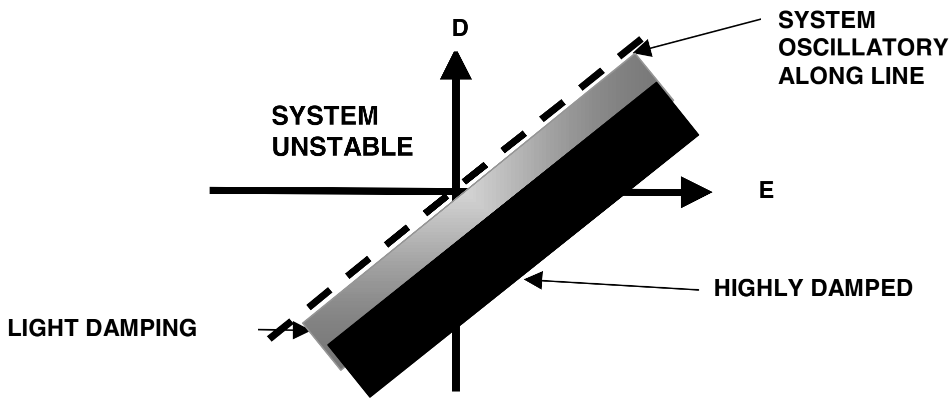


Figure A-6
Effect of variation of control parameters *D* and *E* on the damping of a simple four bus system with a FACTS controller, modeled as a transportation system

A.5 Flow Chart of Transportation Algorithms

Figure A-7 is a flow chart that highlights the steady state transportation power flow / FACTS control calculator.

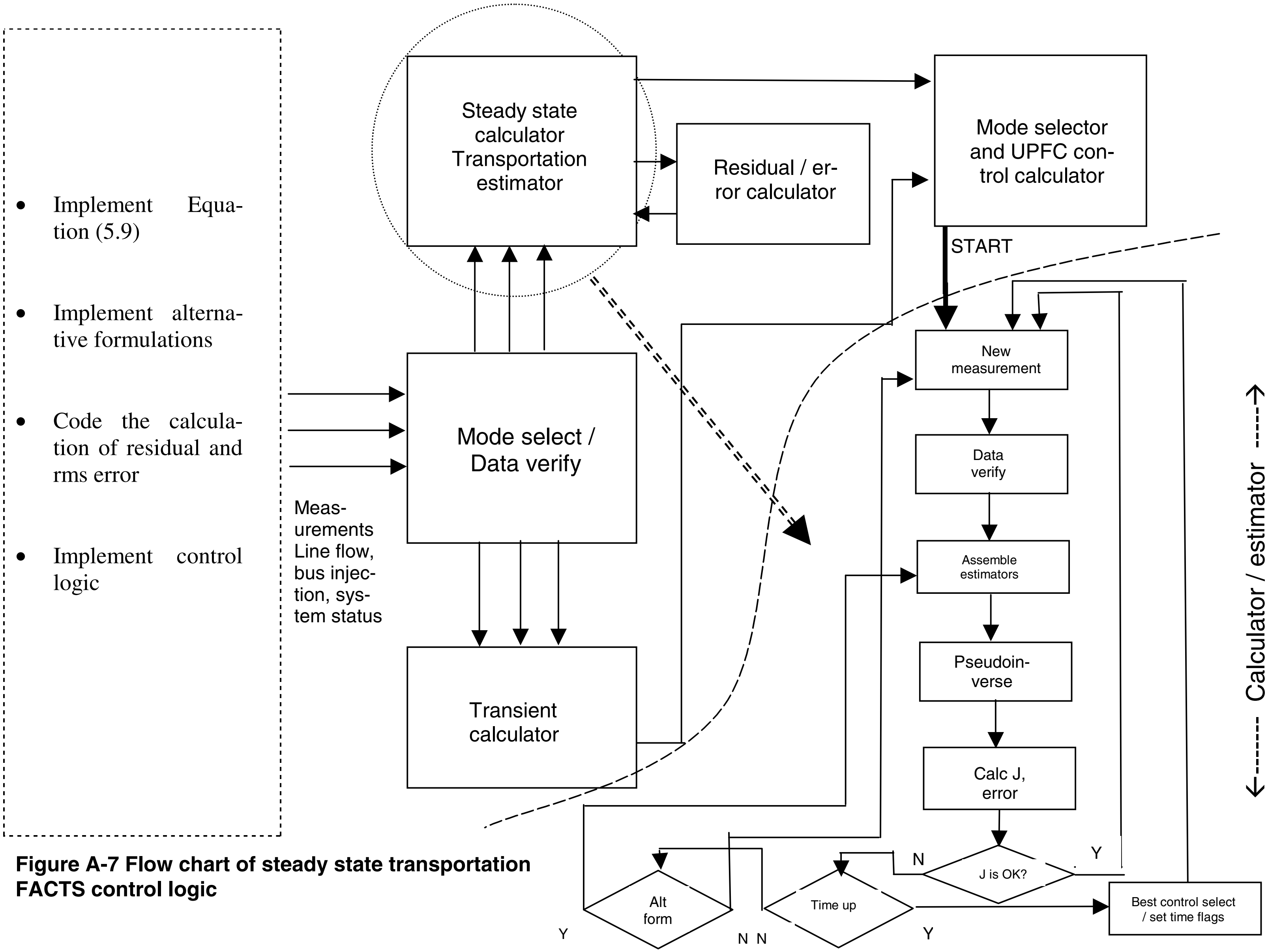


Figure A-7 Flow chart of steady state transportation FACTS control logic

APPENDIX B

THE DEFINITION OF AVAILABLE TRANSMISSION CAPABILITY

B.1 ATC Principals and Definition

This appendix contains a brief summary of the definitions and determination of available transmission capability as found in reference [J8]. This reference is a framework for determining available transmission capabilities in interconnected networks.

The principals behind ATC that govern its measurement and definition are:

- The commercial viability of the concept
- Inclusion of time variation of active power flows in transmission networks
- Dependency on the path of the desired ATC as well as the injection point of active power
- Inclusion of uncertainty.

The term available transfer capability or ATC is defined as the transfer capability remaining in the physical transmission network for further commercial activity over and above already committed uses. Table B-1 contains a summary of related terms. Using these terms, one finds that,

$$ATC = TTC - TRM - CBM - \Sigma(\text{existing transmission commitments}).$$

The determination of transfer capability is based on computer simulations. The main elements in these simulations are:

- Projected customer demands
- Generation dispatch
- System configuration
- Base scheduled transfers
- System contingencies.

Table B-1
Terms relating to available transfer capability summarized from reference [J8]

Term	*Acro-nym*	*Definition*
Available transfer capability	ATC	the transfer capability remaining in the physical transmission network for further commercial activity over and above already committed uses
Total transfer capability	TTC	The amount of electric power that can be transferred over the interconnected transmission network in a reliable manner while meeting all of a specific set of defined pre- and post-contingency system conditions
Transmission reliability margin	TRM	The transfer capability necessary to ensure that the interconnected transmission network is secure under a reasonable range of uncertainties in system conditions
Capacity benefit margin	CBM	The transmission transfer capability reserved by load serving entities to ensure access to generation from interconnected systems to meet generation reliability requirements
Curtailability	-	The right of a transmission provider to interrupt all or part of transmission service due to constraints that reduce the capability of the transmission network to provide that transmission service
Recallability	-	The right of a transmission provider to interrupt all or part of a transmission service for any reason, including economic, that is consistent with FERC policy and the transmission provider's transmission service tariffs or contract provisions
Non-recallable ATC	NATC	TTC – TRM – non-recallable reserved transmission service (including CBM)
Recallable ATC	RATC	TTC – TRM – recallable transmission service – non-recallable transmission service (including CBM)

B.2 Limits to Transfer Capability

Reference [J8] gives the following key limiting factors to transfer capability:

- Thermal limits
- Voltage limits
- Stability limits.

B.3 The Determination of ATC

Reference [J8] gives a method for the determination of ATC known as the related system path method (RSP). The method is applicable for transmission systems that contain generation and load centers that are distant from each other, and that are configured as sparse networks. The RSP method is:

- The determination of the TTC
- Allocation of the TTC among the transmission owners
- Calculation of the ATC for each right-holder by subtracting each of their uses from each of their individual TTC rights.

The RSP method models unscheduled flows and parallel path flows.

An example of the RSP method appears in [J8].

APPENDIX C

IMPLEMENTATION AND EXAMPLES OF FAST SOLUTION METHODS FOR FACTS CONTROLS

C.1 Introduction

The objective of this appendix is to exemplify the main control strategies for steady state and transient FACTS controls using fast solution methods as outlined in Chapter 6. The main illustrations for steady state controls are listed in Table C-1.

Table C-1
Steady state controls for FACTS technologies using fast methods and their illustration

		FACTS device controls these MVA elements		
		Active power P	*Reactive power Q*	*Both P and Q*
Desired to control	Bus phase angles, δ	Example C-1	*	Similar to Example C-1 with control of Q added and control vector repartitioned.
Desired to control	Bus voltage magnitudes, $\|V\|$	*	Examples C-2 and C-3	Similar to Example C-2 with control of P added and control vector repartitioned.
Desired to control	Both δ and $\|V\|$	*	*	Similar to Examples (C.1) and (C.2) with control vector repartitioned.
Desired to control	Active power line flows	Example C-4	*	Similar to Example C-4 with reactive flows modeled.

*Less effective control

C.2 Steady State Control of Bus Phase Angle

In Example C-1, the steady state control of a bus phase angle using a FACTS controller is illustrated. The fast method technology employs one iteration of a Newton-Raphson power flow study. For this example, it is assumed that the FACTS device controls only active power flow in a line. The essence of the Newton method is

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J1 & J2 \\ J3 & J4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta |V| \end{bmatrix}.$$

In this expression, the left hand side is the mismatch active and reactive power given by,

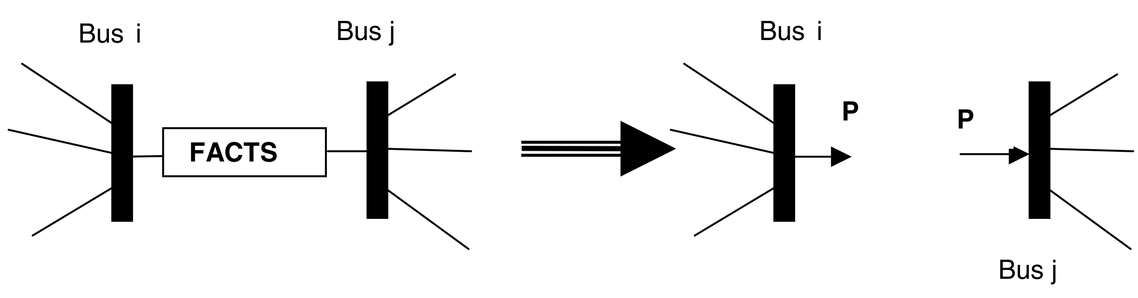
$$\Delta P_i = -\sum_{j=1}^{N} |Y_{ij}||V_i||V_j| \cos(-\theta_{ij} - \delta_j + \delta_i) + P_i$$

$$\Delta Q_i = -\sum_{j=1}^{N} |Y_{ij}||V_i||V_j| \sin(-\theta_{ij} - \delta_j + \delta_i) + Q_i$$

where *Y* refers to the bus admittance matrix magnitudes and ħ refers to the phase angles of the bus admittance matrix entries. The terms P_i and Q_i refer to the specified active and reactive powers at bus *i*. Assuming that the ƛ□ subvector alone is to be partitioned into a controlled portion (subscript *c*) and an uncontrolled portion (subscript *u*),

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = [J] \begin{bmatrix} \Delta\delta_c \\ \Delta\delta_u \\ |V| \end{bmatrix}.$$

Figure C-1 shows the strategy in accommodating the FACTS controller.



FACTS controller inserted in a line *Equivalent circuit*

Figure C-1
Strategy in accommodating a FACTS controller for the control of a bus phase angle in the steady state

The resulting control formula is found using linear state estimation technology, and the control formula is,

$$\begin{bmatrix} +Pctrl \\ -Pctrl \\ \Delta Pu \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_\alpha & J_\beta & J_\gamma \\ J_\delta & J_\varepsilon & J_\zeta \\ J_\eta & J_\theta & J_\iota \\ J_\kappa & J_\lambda & J_\mu \end{bmatrix} \begin{bmatrix} \Delta\delta_C \\ \Delta\delta_U \\ \Delta |V| \end{bmatrix}$$

where the Jacobian matrix is partitioned as need and as shown. This leads to Example C-1. The purpose of these examples is top illustrate how to set-up the control formulas – for this purpose small three bus examples are useful.

Example C-1 Steady state control of bus phase angle using P FACTS control

This is a simple example of an equivalent three bus power system as shown in Figure C-2. This simple system is used also in Examples (C.2) and (C.3). System data and loads for the example appear in Tables C-2 – C-3.

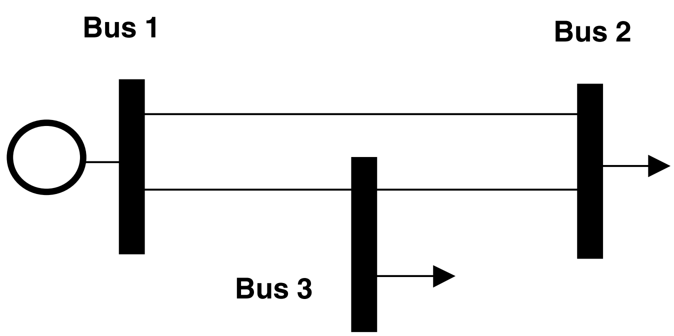


Figure C-2
Equivalent three bus power system for Examples (C.1) – (C.3)

Table C-2
Load and bus data for example

	Load and bus data	
Parameter	Per unit value	Comment
V_1	1.05 +*j* 0.00	Swing bus
S_2	-0.96 +*j* 2.07	Load
S_3	-3.15 +*j* 2.85	Load

Table C-3
Line impedance data for example

	Line impedance	
Line	*R* (pu)	*X* (pu)
1 – 2	0.01	0.01
1 – 3	0.00	0.05
2 - 3	0.00	0.01

The Jacobian matrix for this example using the ordering [ƛP_2, ƛP_3, ƛQ_2, ƛQ_3], [□$_2$, □$_3$, $|V_2|$, $|V_3|$] is (at a flat start of 1.05 per unit voltage profile) [J1],

$$J = \begin{bmatrix} -165.3750 & 110.2500 & 52.5000 & 0.0000 \\ 110.2500 & -132.3000 & 0.0000 & 0.0000 \\ 55.1250 & 0.0000 & -157.5000 & 105.0000 \\ 0.0000 & 0.0000 & 105.0000 & -126.0000 \end{bmatrix}.$$

In this example, a FACTS controller is inserted into line 1 – 2 to force the bus phase angle at bus 2 to be –0.500 degree. In this case the bus admittance matrix magnitude |*Y*| and phase angles ℏ are,

$$|Y| = \begin{bmatrix} 86.023 & 70.711 & 20.000 \\ 70.711 & 158.114 & 100.000 \\ 20.000 & 100.000 & 120.000 \end{bmatrix} \text{ per unit}$$

$$\theta = \begin{bmatrix} = 0.9505 & 2.3562 & 1.5708 \\ 2.3562 & -1.2490 & 1.5708 \\ 1.5708 & 1.5708 & -1.5708 \end{bmatrix} \text{ radians.}$$

The mismatch power and reactive power at the flat start are

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} -0.9600 \\ -3.1500 \\ 2.0700 \\ -2.8500 \end{bmatrix}$$

Calculating the mismatch powers and setting up the equation

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J1 & J2 \\ J3 & J4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix}$$

gives,

$$\begin{bmatrix} \Delta P_2 \\ -3.1500 \\ 2.0700 \\ -2.8500 \end{bmatrix} = \begin{bmatrix} -165.3750 & 110.2500 & 52.5000 & 0.0000 \\ 110.2500 & -132.3000 & 0.0000 & 0.0000 \\ 55.1250 & 0.0000 & -157.5000 & 105.0000 \\ 0.0000 & 0.0000 & 105.0000 & -126.0000 \end{bmatrix} \begin{bmatrix} -0.5000 * (\pi/180) \\ \delta_3 \\ |V_2| \\ |V_3| \end{bmatrix}$$

The Matlab code for the solution is

```
%Example C.1
%Jacobian matrix calculation
%Normally this is calculated from v, |Y|, and
%theta, but in this
%example the Jacobian matrix is hard coded
j=[-165.3750,110.2500,-52.5000,0;...
```

```
        110.2500,-132.3000,0,0;...
        55.1250,0,-157.5000,105.0000;...
        0,0,105.0000,-126.0000];
%Calculation of mismatch powers
%Normally this is done by a formula, but the result
%is hard coded in this simple example
dpdq=[-0.96;-3.15;2.07;-2.85];
%Select out submatrices and subvectors
%according to control formula
a=dpdq(2:4);
b=j(1,1);
c=j(1,2:4);
d=j(2:4,1);
e=j(2:4,2:4);
f=-0.5*pi/180;
z0=[0;0;0];
%Calculate control
soln=inv([-1,c;z0,e])*[-b*f;a-d*f];
%Print control
soln(1)
```

and the solution (i.e., power level setting of the FACTS controller) is found as,

```
» epri0002exC1

ans =

    3.3985
```

In this case, the answer, read as approximately 3.4 per unit, may be reconciled as follows:

- The active power flows in lines 1-3 and 3-2 can be simply calculated in the case of the application of the FACTS control. In this case the system becomes simply radial as shown in Figure C-3, and the flow in 1 – 3 is found to be 0.7115 per unit.

- Application of the lossless lumped transmission line formula for line 1 – 3 gives δ_3 = -1.8491 degrees,

$$P_{ab} = \frac{|V_a||V_b|\sin(\delta)}{x}$$

$$0.7115 = (1.05^2 \sin(\delta))/(0.05)$$

$$\delta = 1.8491 \text{ degrees}$$

- In line 3 – 2, 2.4385 per unit active power flows from bus 2 to bus 3. The transmission line formula gives δ_2 = -0.5817 degree,
-

$$P_{ab} = \frac{|V_a||V_b|\sin(\delta)}{x}$$

$$2.4385 = (1.05^2 \sin(\square))/0.01$$

$$\square = 1.2674$$

$$\square_2 = -1.8491 + 1.2674 = -0.5817 \text{ degree}$$

- Thus the target figure of $\square_2$ = -0.5 degree is approximately attained. Actual power flow solutions give even a closer agreement.

C.3 Steady State Control of Bus Voltage Magnitude

In this development, it is assumed that the FACTS device controls series reactive power flow from bus *i* to bus *j* much like that in Figure C-1. It is also assumed that the bus voltage magnitude is to be controlled. The development follows that of Section (C.2), and the result is,

$$\begin{bmatrix} \Delta P \\ +\Delta Q_c \\ -\Delta Q_c \\ \Delta Q_u \end{bmatrix} = \begin{bmatrix} J_\alpha & J_\beta & J_\gamma \\ J_\delta & J_\varepsilon & J_\zeta \\ J_\eta & J_\theta & J_i \\ J_K & J_\lambda & J_\mu \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\,|\,Vc\,| \\ \Delta\,|\,Vu\,| \end{bmatrix}$$

The basis of the technology is linear state estimation technology for overdetermined systems. From this expression, Example C-2 follows. If the FACTS controller is actually a SVC, the partitioning is different,

$$\begin{bmatrix} \Delta P \\ \Delta Qc \\ \Delta Qu \end{bmatrix} = \begin{bmatrix} J_\alpha & J_\beta & J_\gamma \\ J_\delta & J_\varepsilon & J_\zeta \\ J_\eta & J_\theta & J_\iota \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\,|\,Vc\,| \\ \Delta\,|\,Vu\,| \end{bmatrix}$$

and Example C-3 Follows from this formula.

Example C-2 Steady state control of bus voltage using a series Q FACTS controller using fast methods

In this example, the same sample system is used as in Example C-1. A series FACTS controller is inserted in line 2 – 3, and reactive power in that line is controlled. It is desired to set the bus voltage at $|V_2|$ to 1.06 per unit. This case follows the procedure in Example C-1 closely with the expression

$$\begin{bmatrix} \Delta P_2 \\ \Delta P_3 \\ \Delta Q_2 + Q \\ \Delta Q_3 - Q \end{bmatrix} = [J] \begin{bmatrix} \Delta\delta_2 \\ \Delta\delta_3 \\ 1.06 - 1.05 \\ \Delta V_3 \end{bmatrix}$$

replacing the control equation Example C-1. The Matlab code and solution are:

```
%Example C-2
%Jacobian matrix calculation
%Normally this is calculated from v, |Y|,
%and theta, but in this
%example the Jacobian matrix is hard coded
j=[-165.3750,110.2500,-52.5000,0;...
      110.2500,-132.3000,0,0;...
      55.1250,0,-157.5000,105.0000;...
      0,0,105.0000,-126.0000];
%Calculation of mismatch powers
%Normally this is done by a formula, but the
%result is hard coded in this simple example
dpdq=[-0.96;-3.15;2.07;-2.85];
%Select out submatrices and subvectors
%according to control formula
a=j(1:2,1:2);
b=j(1:2,2);
c=j(1:2,3);
d=j(3,1:2);
e=j(3,3);
f=j(3,4);
g=j(4,1:2);
h=j(4,3);
i=j(4,4);
z0=[0;0];
%Specify desired voltage at bus 2
v2s=1.06;
%Calculate delta v2
deltav2=v2s-1.05;
%Calculate control
soln=inv([a,c,z0;d,f,-1;g,i,1])...
   *[dpdq(1:2);dpdq(3)-e*deltav2;dpdq(4)-
 h*deltav2];
%Print control
soln(4)
```

The solution is,

```
» epri0002exC2
ans =
    2.2435
```

The reactive power setting of the FACTS controller is approximately 2.24 per unit as verified by power flow studies.

Example C-3 Steady state control of bus voltage amplitude using a SVC

In this example, the same sample system of Example C-1 is used. A static var compensator is located at bus 2 and it is set to produce $|V_2|$ at 1.06 per unit. The Jacobian matrix for the system is

$$J = \begin{bmatrix} -165.3750 & 110.2500 & 52.5000 & 0.0000 \\ 110.2500 & -132.3000 & 0.0000 & 0.0000 \\ 55.1250 & 0.0000 & -157.5000 & 105.0000 \\ 0.0000 & 0.0000 & 105.0000 & -126.0000 \end{bmatrix}.$$

and the inverse Jacobian matrix is

$$J^{-1} = \begin{bmatrix} -0.0087 & -0.0073 & 0.0065 & 0.0054 \\ -0.0073 & -0.0136 & 0.0054 & 0.0045 \\ -0.0069 & -0.0057 & -0.0091 & -0.0076 \\ -0.0057 & -0.0048 & -0.0076 & -0.0143 \end{bmatrix}.$$

and the SVC control signal is calculated to be

$$\lambda Q_2 = 1.099 \text{ per unit.}$$

C.4 Steady State Line Flow Control

The UPFC is generally proposed to control line flows. The controlled flows may be used to control not only the flow in the line in which the UPFC is inserted, but also in remote lines. A formulation using the transportation method is illustrated in Example C-4. The basis of the method is Equation (5.1) repeated here as Equation C-1,

$$F_{node} = [L]F_{branch}. \tag{C.1}$$

Example C-4 Control of remote line flows using the control of active power flow in one line

Consider the nine bus, twelve line illustrative system depicted in Figure C-3. For this system, the bus injections are,

$$P_{bus}^{A} = \begin{bmatrix} 2.0 \\ 0.5 \\ -0.5 \\ -2.0 \\ 0 \\ 0.2 \\ -0.1 \\ 0 \\ -0.1 \end{bmatrix}$$

where negative numbers refer to actual active power loads, and positive numbers refer to generated injections of active powers, all in per unit. The superscript *A* refers to a base case operating strategy (case *B* will be discussed momentarily). Using the line direction notation in Figure C-3, the line flows are found from a power flow study as,

$$P_{line}^{A} = \begin{bmatrix} 1.00 \\ 0.50 \\ 1.00 \\ 1.00 \\ 0.00 \\ -1.00 \\ 1.00 \\ 0.00 \\ -1.00 \\ 1.20 \\ -0.10 \\ -1.10 \end{bmatrix}$$

Again, the notation is in per unit with the active power shown. For this example, the line – bus incidence matrix *L* is,

$$L = \begin{bmatrix} 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & -1 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & -1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & -1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & -1 \end{bmatrix}$$

Consider now a FACTS controlled case, case *B*, in which a UPFC is inserted in line 7. And further consider that the control in line 7 is to actually control two remote lines, namely lines 1 and 6. The desired control is

$$P_{line1}^{B} = 1.10 \qquad\qquad P_{line6}^{B} = -1.30$$

The superscript *B* notation refers to the FACTS controlled case. Then Equation (C.1) becomes,

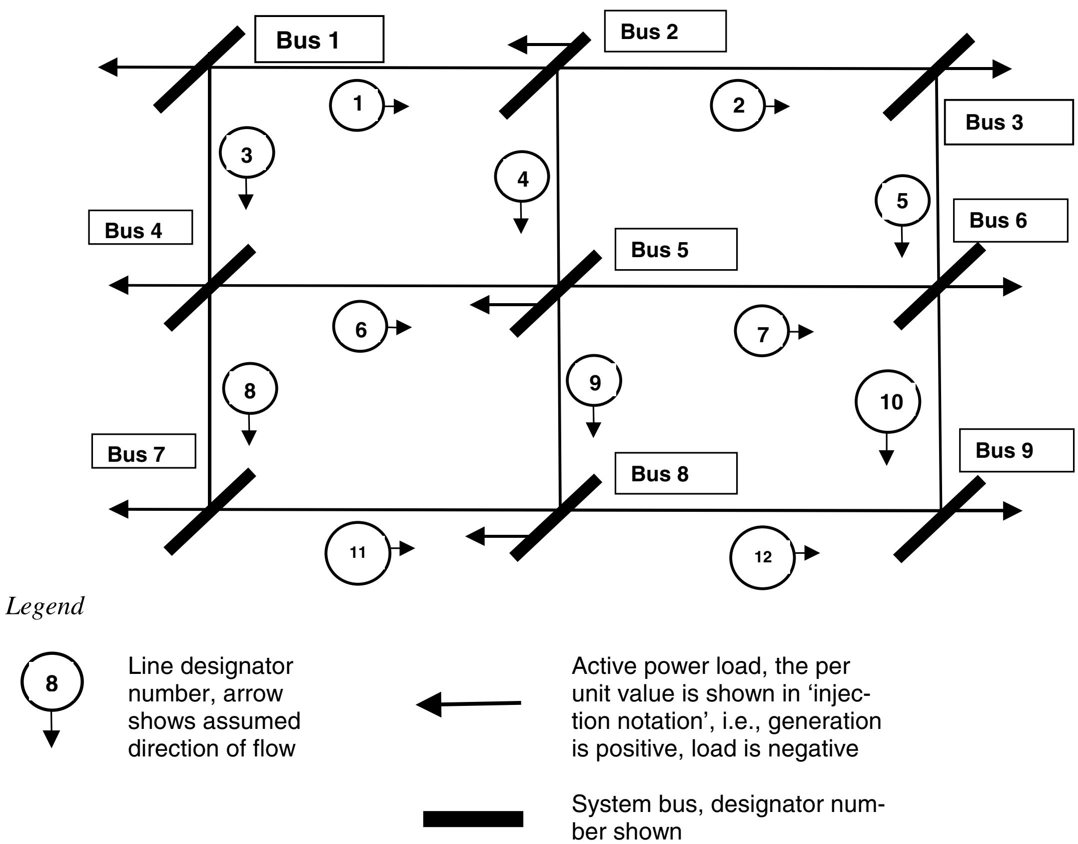


Figure C-3
Illustrative power system used in Example C-4

$$
\begin{bmatrix} P^B_{bus1} \\ \dots \\ P^B_{bus9} \end{bmatrix} = \begin{bmatrix} & & \dots & & \\ A & B & C & D & E \\ & & \dots & & \end{bmatrix} \begin{bmatrix} P^B_{line1} \\ P^B_{line2} \\ \dots \\ P^B_{line5} \\ P^B_{line6} \\ P^B_{line7} \\ P^B_{line8} \\ \dots \\ P^B_{line12} \end{bmatrix} \begin{matrix} \leftarrow Given \\ \\ \leftarrow Subvector\ F \\ \\ \leftarrow Given\ controlled \\ \Leftarrow FACTS\quad device \\ \\ \leftarrow Given\quad G \\ \\ \end{matrix}
$$

where *A, B, D, E, F* refer to partitions of the incidence matrix *L,* subvector *F* is ‘floating’, and subvector *G* is given line loads that are not controlled. The base case subvectors of the line flow vector are,

$$P_{line1}^{A} = \begin{bmatrix} 1.00 \end{bmatrix} \qquad P_{line6}^{A} = \begin{bmatrix} -1.00 \end{bmatrix}$$

$$P_{line7}^{A} = \begin{bmatrix} 1.00 \end{bmatrix}$$

$$F = \begin{bmatrix} 1.00 \\ 0.50 \\ 1.00 \\ 1.00 \end{bmatrix} \qquad G = \begin{bmatrix} 0.00 \\ -1.00 \\ 1.20 \\ -0.10 \\ -1.10 \end{bmatrix}$$

For this example, the linear state estimator of the control, namely P_{line7}^{B} is

$$P_{line7}^{A} = \quad D^{+}(P_{bus}^{B} - AP_{line1}^{B} - BF - CP_{line6}^{B} - EG)$$

and assuming that the bus injections (loads) are not changed from case A to case B, one obtains the Matlab formulation as follows,

```
%Example C.4
%Example to show the control of active power flow in two
%remote lines using
%a UPFC controller.
%Calculate the line - bus incidence matrix (normally this
%is built from line data -- it is hard coded here)
l=[1,0,1,0,0,0,0,0,0,0,0,0;...
      -1,1,0,1,0,0,0,0,0,0,0,0;...
      0,-1,0,0,1,0,0,0,0,0,0,0;...
      0,0,-1,0,0,1,0,1,0,0,0,0;...
      0,0,0,-1,0,-1,1,0,1,0,0,0;...
      0,0,0,0,-1,0,-1,0,0,1,0,0;...
      0,0,0,0,0,0,0,-1,0,0,1,0;...
      0,0,0,0,0,0,0,0,-1,0,-1,1;...
      0,0,0,0,0,0,0,0,0,-1,0,-1];
%Construct the required submatrices
a=l(:,1);
b=l(:,2:5);
c=l(:,6);
d=l(:,7);
e=l(:,8:12);
%Enter initial line flow subvectors and bus load vector
pb=[2.00;0.50;-0.50;-2.00;0;0.20;-0.10;0;-0.10];
p1b=[1.1];
p6b=[-1.3];
f=[1.00;0.50;1.00;1.00];
g=[0.00;-1.00;1.20;-0.10;-1.10];
%Use linear state estimator formula to calculate UPFC command
%in this case this is the command flow in line 7
p7b=Pinv(d)*(pb-a*p1b-b*f-c*p6b-e*g);
%print result
```

```
    p7b
```

And the solution is found as,

```
» epri0002exc4

p7b =

    0.3500
```

In Example C-4 state estimation error can be calculated simply as

$$Error = DP_{line7}^{A} - \quad (P_{bus}^{B} - AP_{line1}^{B} - BF - CP_{line6}^{B} - EG)$$

This was done in Matlab, and the result is approximately 0.3 per unit (root mean square error). Note that in this case, no measurements were use to develop the FACTS control, and no weights were used to develop this signal. Also, the single UPFC is used to control two line flows.

REFERENCES

Note: references are organized according to:

[A] Steady state modeling and analysis
[B] OPF and dispatch
[C] Steady state specialized control structures
[D] Device applications and placement (steady state)
[E] Transient modeling and analysis
[F] Transient stability
[G] Transient specialized control structures
[H] Device applications and placement (transient)
[I] Coordinated controls
[J] General references

[A] Steady State Modeling and Analysis

[A1] Gotham, D. J.; Heydt, G. T., "Power flow control and power flow studies for systems with FACTS devices," IEEE Transactions on Power Systems, Volume 131, Feb. 1998, pp. 60 –65.

[A2] Stahlkopf, K.E.; Wilhelm, M. R., "Tighter controls for busier systems [power systems]," IEEE Spectrum, Volume 34 4, April 1997, pp. 48 - 52.

[A3] Fuerte-Esquivel, C.R.; Acha, E., "Newton-Raphson algorithm for the reliable solution of large power networks with embedded FACTS devices," Proceedings-IEE on Generation, Transmission and Distribution, Volume 143 5, Sept. 1996, pp. 447 – 454.

[A4] Edris, A.; Mehraban, A. S.; Rahman, M.; Gyugyi, L.; Arabi, S.; Reitman, T. "Controlling the flow of real and reactive power," IEEE Computer Applications in Power, Volume 11 1, Jan. 1998, pp. 20 –25.

[A5] Wildberger, A. M., "Overview of exploratory research in soft computing applications to power systems at the Electric Power Research Institute," IEEE International Conference on Systems, Man and Cybernetics, 1995, Intelligent Systems for the 21st Century, pp. 2007 - 2012 Volume 3.

[A6] Berizzi, A.; Silvestri, A.; Tironi, E.; Zaninelli, D.; Marannino, P., "Power flows and voltage control in electric systems by traditional and innovative devices," Electrotechnical Conference, 1996. MELECON '96, 8th Mediterranean Volume 3, 1996, pp. 1620 - 1626 Volume 3.

[A7] Sutanto, D., "A review of new innovations in power system control," Proceedings of 1995 International Conference on Power Electronics and Drive Systems, 1995, pp. 694 - 699 Volume 2.

[A8] Zhang, B. M.; Ding, Q. F., "The development of FACTS and its control," Fourth International Conference on Advances in Power System Control, Operation and Management, 1997. APSCOM- 97. (Conference Publication No. 450), pp. 48 - 53 Volume 1.

[A9] Laughton, M. A., "Influences on developments in power system operation," APSCOM- 97, Fourth International Conference on Advances in Power System Control, Operation and Management, 1997, (Conference Publication No. 450) pp. 7 - 13, Volume 1.

[A10] Hingorani, N. G., "FACTS technology and opportunities," IEE Colloquium on Flexible AC Transmission Systems (FACTS) - The Key to Increased Utilization of Power Systems, (Digest No. 1994/005), 1994, pp. 4/1 –4/10.

[A11] Papantoniou, A.; Coonick, A., "Simulation of FACTS for wind farm applications," IEE Colloquium on Power Electronics for Renewable Energy (Digest No: 1997/170), 1997, pp. 8/1 - 8/5 .

[A12] Akdag, A.; Minakata, H.; Tadakuma, S., "Simulation study of a unified power flow controller via personal computer based hybrid simulator," Conference Record of the 1999 IEEE Industry Applications Conference, 1999. Thirty-Fourth IAS Annual Meeting. pp. 456 – 462, Volume 1.

[A13] Spee, R.; Zhu, W., "Flexible AC transmission systems simulation and control," AFRICON '92 Proceedings, 1992, pp. 65 –68.

[A14] Ishigame, A.; Takagi, Y.; Kawamoto, S.; Taniguchi, T.; Tanaka, H., "Structural control based on genetic algorithm and neural network for electric power systems," Proceedings of the Second International Forum on Applications of Neural Networks to Power Systems, 1993, ANNPS '93, pp. 169 –174.

[A15] Hingorani, N. G., "Flexible AC transmission," IEEE Spectrum, Volume 30 4, April 1993, pp. 40 - 45.

[A16] Ewart, D. N.; Koessler, R. J.; Mountford, J. D.; Maratukulam, D., "FACTS options permit the utilization of the full thermal capacity of AC transmission," International Conference on AC and DC Power Transmission, 1991, 1991, pp. 13 – 18.

[A17] Gronquist, J. F.; Hiskens, I. A., "On the application of FACTS controllers derived from lossless models to lossy systems," Proceedings of the 35th IEEE Conference on Decision and Control, Volume 3, 1996, pp. 3459 - 3463, Volume 3.

[A18] Cooper, C. B.; Ekanayake, J. B.; Jenkins, N.; Putrus, G. A., "Modeling plant for flexible AC transmission systems," IEE Colloquium on Flexible AC Transmission Systems (FACTS) - The Key to Increased Utilization of Power Systems, (Digest No. 1994/005), 1994, pp. 3/1 - 3/3.

[A19] Therond, P.; Cholley, P.; Daniel, D.; Joncquel, E.; Lafon, L.; Poumarede, C., "FACTS research and development program at EDF," IEE Colloquium on Flexible AC Transmission Systems (FACTS) - The Key to Increased Utilization of Power Systems, (Digest No. 1994/005), 1994, pp. 6/1 –6/5.

[A20] Gotham, D. J., "Flexible AC transmission systems in power network analysis and for power flow control," Ph.D. Thesis, Purdue University, West Lafayette, IN, December, 1996.

[A21] Ardito, A.; Bresesti, P.; Cova, B.; Giornelli, F.; Lusvarghi, R.; Li Qi Sheng, "Modern analysis criteria and software tools for planning large interconnected systems," International Conference on Power System Technology, 1998. Proceedings. POWERCON '98, 1998, pp. 951 - 855, Volume 2.

[A22] Gronquist, J.; Sethares, W.; Alvarado, F.; Lasseter, R., "Animated vectors for visualization of power system phenomena," IEEE Transactions on Power Systems, Volume 11 1, Feb. 1996, pp. 267 - 273

[A23] Fuerte-Esquivel, C. R.; Acha, E.; Tan, S. G.; Rico, J. J., "Efficient object oriented power systems software for the analysis of large-scale networks containing FACTS-controlled branches," IEEE Transactions on Power Systems, Volume 13 2, May 1998, pp. 464 –472.

[A24] Fuerte-Esquivel, C. R.; Acha, E., "A Newton-type algorithm for the control of power flow in electrical power networks," IEEE Transactions on Power Systems, Volume 12 4, Nov. 1997, pp. 1474 –1480.

[A25] Vernotte, J. F.; Panciatici, P.; Meyer, B.; Antoine, J. P.; Deuse, J.; Stubbe, M., "High fidelity simulation of power system dynamics," IEEE Computer Applications in Power, Volume 8 1, Jan. 1995, pp. 37 – 41.

[A26] Gotham D.; Heydt, G., "FACTS device models for power flow studies," Proceedings 27th North American Power Symposium, Bozeman, MT, Oct 2 – 3, 1995, pp. 514 – 519.

[A27] Ye, Y.; Kazerani, M., "Operating constraints of FACTS devices," Proceedings IEEE Summer Power Meeting, Seattle, WA, July 2000, paper 0-7803-6423-6/00.

[A28] Yang, Z.; Shen C.; Crow, M.; Zhang, L., "An improved STATCOM model for power flow analysis," Proceedings IEEE Summer Power Meeting, Seattle, WA, July 2000, paper 0-7808-6409-6/00.

[B] OPF and Dispatch

[B1] Ge Shaoyuan; Chung, T. S., "Coupled active power dispatch with FACTS devices and specified power flow control constraints," Fourth International Conference on Advances in Power System Control, Operation and Management, 1997, APSCOM- 97. (Conference Publication No. 450) pp. 678 - 683 Volume 2.

[B2] Chung, T. S.; Ge Shaoyun, "Optimal power flow incorporating FACTS devices and power flow control constraints," Proceedings. POWERCON'98, International Conference on Power System Technology, 1998, pp. 415 – 419, Volume 1.

[B3] Taranto, G. N.; Pinto, L. M. V .G.; Pereira, M. V. F., "Representation of FACTS devices in power system economic dispatch," IEEE Transactions on Power Systems, Volume 7 2, May 1992, pp. 572 –576.

[B4] Ge, S. Y.; Chung, T. S., "Optimal active power flow incorporating power flow control needs in flexible AC transmission systems," IEEE Transactions on Power Systems, Volume 14 2, May 1999, pp. 738 –744.

[B5] Preedavichit, P.; Srivastava, S. C., "Optimal reactive power dispatch considering FACTS devices," Fourth Volume 2, 1997, pp. 620 - 625, Volume 2.

[B6] Ge, S. Y.; Chung, T. S.; Wong, Y. K., "A new method to incorporate FACTS devices in optimal power flow," 1998 International Conference on Energy Management and Power Delivery, 1998, Proceedings of EMPD '98, pp. 122 - 127 Volume 1.

[B7] Huang, G.; Hsieh, S.-C., "Fast textured algorithms for optimal power delivery problems in deregulated environments," IEEE Transactions on Power Systems, Volume 13 2, May 1998, pp. 493 –500.

[B8] Aredes, M.; Watanabe, E. H., “New control algorithms for series and shunt three-phase four-wire active power filters,” IEEE Transactions on Power Delivery, Volume 10 3, July 1995, pp. 1649 –1656.

[B9] Kamwa, I.; Grondin, R.; Asber, D.; Gingras, J. P.; Trudel, G., “Large-scale active-load modulation for angle stability improvement,” IEEE Transactions on Power Systems, Volume 14 2, May 1999, pp. 582 –590.

[B10] Papic, I.; Zunko, P.; Povh, D.; Weinhold, M., “Basic control of unified power flow controller,” IEEE Transactions on Power Systems, Volume 12 4, Nov. 1997, pp. 1734 –1739.

[B11] Lai, L. L.; Ma, J. T., “Power flow control with UPFC using genetic algorithms,” International Conference on Intelligent Systems Applications to Power Systems, 1996. Proceedings, ISAP '96., 1996, pp. 373 –377.

[B12] Dancachi N.; Rawlins M.; Alsac O.; Prais M.; Stott B., “OPF for reactive pricing studies on the NGC system,” IEEE Transactions on Power Systems, Volume 11, No. 1, February 1996, pp. 350 – 356.

[B13] Lim, J.; Moon, S., “UPFC operation for the minimization of power production and delivery costs,” Proceedings IEEE Summer Power Meeting, Seattle, WA, July 2000.

[B14] Duan, X.; Chen, J.; Peng, F.; Luo Y.; Huang, Y., “Power flow control with FACTS devices,” Proceedings IEEE Summer Power Meeting, Seattle, WA, July 2000, paper 0-7803-6423-6/00.

[C] Steady State Specialized Control Structures

[C1] Hiyama, T.; Kihara, H.; Miyauchi, H.; Ortmeyer, T. H., “Fuzzy logic switching of FACTS devices for stability enhancement,” Circuits and Systems, 1996. ISCAS '96, 1996 Proceedings of IEEE International Symposium on Connecting the World, pp. 605 –608, Volume 1.

[C2] Lu Qiang; Sun Yuanzhang; Shen Chen; Mei Shengwei; Konishi, H., “Target oriented intelligent predictive evaluating control approach for FACTS devices,” 1998 International Conference on Power System Technology, POWERCON '98, pp. 389 - 394 Volume 1.

[C3] Chen, D.; Mohler, R.; Chen, L., “Neural-network-based adaptive control with application to power systems,” Proceedings of the 1999 American Control Conference, pp. 3236 - 3240 Volume 5.

[C4] Chen Chaoying; Chen Yong; Duan Xuefei; Chen Liyi, “Study of protective relay's behaviors in Unified Power Flow Controller of FACTS,” Fourth International Conference on Advances in Power System Control, Operation and Management, 1997, APSCOM- 97. (Conference Publication No. 450) pp. 632 – 637, Volume 2.

[C5] Wang, H. F.; Li, F., “FACTS control by sampled regulator design,” AFRICON, 1999 IEEE pp. 469 - 474 Volume 1.

[C6] Chen, D.; Mohler, R., “Nonlinear adaptive control with potential FACTS applications,” Proceedings of the 1999 American Control Conference, 1999, pp. 1077 – 1081, Volume 2.

[C7] Palmer, E.; Ledwich, G., “Switching control for power systems with line losses,” IEE Proceedings - Generation, Transmission and Distribution, Volume 146 5, Sept. 1999, pp. 435 –440.

[C8] Wang, H. F.; Li, F.; Cameron, R. G., “FACTS control design based on power system nonparametric models,” IEE Proceedings- Generation, Transmission and Distribution, Volume 146 5, Sept. 1999, pp. 409 –415.

[C9] Aredes, M.; Heumann, K.; Watanabe, E. H., “An universal active power line conditioner,” IEEE Transactions on Power Delivery, Volume 13 2, April 1998, pp. 545 –551.

[C10] Westermann, D.; Rahmani, M.; Stemmler, H.; Beer, A., “Customized FACTS devices for cost effective system solutions,” 1998 International Conference on Power System Technology, 1998. Proceedings. POWERCON '98, pp. 313 - 317 Volume 1.

[C11] Funato, H.; Kawamura, A., “Control of variable active-passive reactance (VAPAR) and negative inductance,” Power Electronics Specialists Conference, PESC '94 Record., 25th Annual IEEE, 1994, pp. 189 - 196, Volume 1.

[C12] Kin-Ho Chu; Pollock, C., “Series compensation on power system with very low harmonic distortion,” IEEE Transactions on Power Delivery, Volume 14 2, April 1999, pp. 512 – 518.

[C13] Lehn, P.W.; Iravani, M. R., “Experimental evaluation of STATCOM closed loop dynamics,” IEEE Transactions on Power Delivery, Volume 13 4, Oct. 1998, pp. 1378 – 1384.

[C14] Yiqiang Chen; Boon-Teck Ooi, “Multimodular multilevel rectifier/inverter link with independent reactive power control,” IEEE Transactions on Power Delivery, Volume 13 3, July 1998, pp. 902 –908.

[C15] Rastogi, M.; Mohan, N.; Edris, A.-A., "Hybrid-active filtering of harmonic currents in power systems," IEEE Transactions on Power Delivery, Volume 10 4, Oct. 1995, pp. 1994 –2000.

[C16] Schauder, C.; Gernhardt, M.; Stacey, E.; Lemak, T.; Gyugyi, L.; Cease, T. W.; Edris, A., "Development of a !100 MVAr static condenser for voltage control of transmission systems," IEEE Transactions on Power Delivery, Volume 10 3, July 1995, pp. 1486 – 1496.

[C17] Nabae, A.; Yamaguchi, M., "Suppression of flickers in an arc-furnace supply system by an active capacitance-a novel voltage stabilizer in power systems," Conference Record of the Power Conversion Conference, Yokohama, 1993, pp. 653 – 658.

[C18] Luciano, A. M.; Lauria, D.; Napoli, E., "Algorithm for automatic generation of fuzzy rules applied to power system controllers," Generation, Transmission and Distribution, IEE Proceedings, Volume 145 2, March 1998, pp. 161 – 167.

[C19] Chu, K.-H.; Pollock, C., "PWM-controlled series compensation with low harmonic distortion," IEE Proceedings - Generation, Transmission and Distribution, Volume 144 6, Nov. 1997, pp. 555 – 563.

[C20] Ishimaru, M.; Okada, N.; Yokoyama, R.; Shirai, G., "Output feedback TCSC controller design making use of linear matrix inequality," Proceedings IEEE Summer Power Meeting, Seattle, WA, July 2000, paper 0-7803-6423-6/00.

[C21] Kim, S.; Lim, J.; Moon, S., "Enhancement of power system security level through the power flow control of UPFC," Proceedings IEEE Summer Power Meeting, Seattle, WA, July 2000.

[C22] Ammari, S.; Besanger, Y.; Hadjsaid, N.; Georges, D., "Robust solutions for the interaction phenomena between dynamic loads and FACTS controllers," Proceedings IEEE Summer Power Meeting, Seattle, WA, July 2000, paper 0-7803-6423-6/00.

[C23] Xiao, Y.; Song, Y.; Sun, Y., "Application of stochastic programming for available transfer capability enhancement using FACTS devices," Proceedings IEEE Summer Power Meeting, Seattle, WA, July 2000.

[D] Device Applications and Placement (Steady State)

[D1] Padiyar, K. R.; Uma Rao, K., "Discrete control of TCSC for stability improvement in power systems," Proceedings of the 4th IEEE Conference on Control Applications, 1995, pp. 246 –251.

[D2] Dolan, P. S.; Smith, J. R.; Mittelstadt, W. A., "Prony analysis and modeling of a TCSC under modulation control," Proceedings of the 4th IEEE Conference on Control Applications, 1995, pp. 239 –245.

[D3] Jenkins, N., "Power electronics applied to the distribution system Flexible AC Transmission Systems - The FACTS" (Ref. No. 1998/500), IEE Colloquium, 1998, pp. 3/1 - 3/7.

[D4] Baker, M. H.; Trow, R. J., "New FACTS controllers and how to assess them," Fourth International Conference on Advances in Power System Control, Operation and Management, 1997. APSCOM- 97. (Conference Publication No. 450), pp. 42 – 47, Volume 1.

[D5] Petitclair, P.; Bacha, S.; Ferrieux, J.-P., "Optimized linearization via feedback control law for a STATCOM," Conference Record of the IEEE Industry Applications Conference, 1997, Thirty-Second IAS Annual Meeting, IAS '97, pp. 880 - 885 Volume 2.

[D6] Petitclair, P.; Besanger, Y.; Bacha, S.; Hadjsaid, N., "FACTS modeling and control: applications to the insertion of a STATCOM on power system," Conference Record of the IEEE Industry Applications Conference, 1997. Thirty-Second IAS Annual Meeting, IAS '97, pp. 2213 - 2217 Volume 3.

[D7] Fuerte-Esquivel, C. R.; Acha, E., "Unified power flow controller: a critical comparison of Newton-Raphson UPFC algorithms in power flow studies," IEE Proceedings - Generation, Transmission and Distribution, Volume 144 5, Sept. 1997, pp. 437 – 444.

[D8] Leung, K. K.; Sutanto, D., "Improving power system operations and control utilizing energy storage," Fourth International Conference on Advances in Power System Control, Operation and Management 1997. APSCOM- 97, (Conference Publication No. 450) pp. 626 - 631, Volume 2.

[D9] Ngan, H. W., "Modeling static phase shifters in multi-machine power systems," Fourth International Conference Advances in Power System Control, Operation and Management, APSCOM- 97 (Conference Publication No. 450), Volume 2, 1997, pp. 785 - 790. Volume 2.

[D10] Rent, K.; Thumm, G.; Weiss, S., "Advanced series compensator enhances flexibility for AC transmission systems," 2nd International Conference on Advances in Power System Control, Operation and Management, APSCOM- 93, 1993, pp. 584 - 591, Volume 2.

[D11] Pereira, M.; Renz, K.; Unterlass, F., "Digital protection schemes of advanced series compensators," 2nd International Conference on Advances in Power System Control, Operation and Management, APSCOM- 93, 1993, pp. 592 – 600, Volume 2.

[D12] Song, Y. H.; Johns, A. T.; Aggarwal, R. K., "Nonlinear thyristor-controlled static VAr compensation," Fifth European Conference on Power Electronics and Applications, 1993, pp. 6 - 60 Volume 8.

[D13] Rios, M.; Hadjsaid, N.; Georges, D.; Fuelled, R.; Torres, A.; Snyder, A., "LQG decentralized controls for facts based on structure of modeling by subsystems," International Conference on Electric Power Engineering, PowerTech Budapest 99, 1999, pp. 305 - 305

[D14] Xioming Yuban; Orglmeister, G.; Merk, W., "Managing the DC link neutral potential of the three-phase-four-wire neutral-point-clamped (NPC) inverter in FACTS applications," Industrial Electronics Society, 1999. IECON '99 Proceedings. The 25th Annual Conference of the IEEE Volume 2, 1999, pp. 571 - 576, Volume 2.

[D15] Adhikari, T., "Application of power electronics in the transmission of electrical energy," TENCON '98. 1998 IEEE Region 10 International Conference on Global Connectivity in Energy, Computer, Communication and Control, pp. 522 - 530, Volume 2.

[D16] Belacheheb, K.; Saadate, S., "UPFC control for line power flow regulation," Proceedings 8th International Conference On Harmonics and Quality of Power Proceedings, Volume 2, 1998, pp. 660 - 664, Volume 2.

[D17] Nabae, A.; Nakajima, Y.; Cao, L.; Tanaka, T.; Ariga, S., "A series active capacitance for compensating voltage drops caused by source," Power Electronics Specialists Conference, 1997. PESC '97, Record., 28th Annual IEEE, pp. 351 – 355, Volume 1.

[D18] Ooi, B. T.; Kazerani, M.; Marceau, R.; Wolanski, Z.; Galiana, F. D.; McGillis, D.; Joos, G., "Mid-point siting of FACTS devices in transmission lines," IEEE Transactions on Power Delivery, Volume 12 4, Oct. 1997, pp. 1717 –1722.

[D19] Enslin, J. H.R .; Jian Zhao; Spee, R., "Operation of the unified power controller as harmonic isolator," Power Electronics Specialists Conference, PESC '94 Record., 25th Annual IEEE, 1994, pp. 169 - 176 Volume 1.

[D20] Enslin, J. H. R.; Zhao, J.; Spee, R., "Operation of the unified power flow controller as harmonic isolator," IEEE Transactions on Power Electronics, Volume 11 6, Nov. 1996, pp. 776 –784.

[D21] Renz, B. A.; Keri, A.; Mehraban, A. S.; Schauder, C.; Stacey, E.; Kovalsky, L.; Gyugyi, L.; Edris, A., "AEP unified power flow controller performance," IEEE Transactions on Power Delivery, Volume 14 4, Oct. 1999, pp. 1374 –1381.

[D22] Sonnenmoser, A.; Lehn, P. W., "Line current balancing with a unified power flow controller," IEEE Transactions on Power Delivery, Volume 14 3, July 1999, pp. 1151 –1157.

[D23] Lie, T. T., "Method of identifying the strategic placement for compensation devices," IEEE Transactions on Power Systems, Volume 10 3, Aug. 1995, pp. 1448 –1453.

[D24] Iravani, M. R.; Maratukulam, D., "Review of semiconductor-controlled (static) phase shifters for power systems applications," IEEE Transactions on Power Systems, Volume 9 4, Nov. 1994, pp. 1833 –1839.

[D25] Nabae, A.; Yamaguchi, M., "Suppression of flicker in an arc-furnace supply system by an active capacitance-a novel voltage stabilizer in power systems," IEEE Transactions on Industry Applications, Volume 31 1, Jan.-Feb. 1995, pp. 107 – 111.

[D26] Gun-Woo Moon; Suk-Ho Yoon, "Predictive current control of distribution static condenser (D-STATCON) for reactive power compensation in flexible AC transmission system (FACTS)," Power Electronics Specialists Conference, 1998, PESC 98 Record. 29th Annual IEEE pp. 816 –822, Volume 1.

[D27] Hojo, M.; Mitani, Y.; Tsuji, K., "Voltage and power swing stabilization by decoupled control with AVR and phase shifter," Proceedings of EMPD '98, International Conference on Energy Management and Power Delivery, 1998, pp. 183 – 188.

[D28] Leung, K. K.; Sutanto, D., "A new topology of a battery energy storage system," Proceedings of EMPD '98, International Conference on Energy Management and Power Delivery, 1998, pp. 253 - 258 Volume 1.

[D29] Watanabe, E.; Aredes, M., "Compensation of non-periodic currents using the instantaneous power theory," Proceedings IEEE Summer Power Meeting, Seattle, WA, July 2000, paper 0-7803-6423-6/00.

[D30] Yang, Z.; Crow, M.; Shen, C.; Zhang, L., "The steady state characteristics of a STATCOM with energy storage," Proceedings IEEE Summer Power Meeting, Seattle, WA, July 2000, paper 0-7803-6423-6/00.

[D31] Han, B.; Moon, S.; Karady, G., "Dynamic characteristic analysis of multi-bridge PWM inverter for SSSC," Proceedings IEEE Summer Power Meeting, Seattle, WA, July 2000.

[D32] Chen, J.; Wang, X.; Duan, X.; Wamng, D.; Zhang, R., "Application of FACTS devices for the interconnected line between Fujian network and Huadong network," Proceedings IEEE Summer Power Meeting, Seattle, WA, July 2000.

[D33] Fardanesh, B.; Shperling, B.; Uzunovic, E.; Zelingher, S., "Multi-converter FACTS devices: the generalized unified power flow controller (GUPFC)," Proceedings IEEE Summer Power Meeting, Seattle, WA, July 2000, paper 0-7803-6403-6/00.

[D34] Fardanesh, B.; Henderson, M.; Shperling, B.; Zellingher, S.; Gyugyi, L.; Schauder, C.; Lam, B.; Mountford, J.; Adapa, R.; Edris, A., "Convertible static compensator application to the New York transmission system," CIGRÉ, Paris, 1`998, paper 14-103.

[D35] Gyugyi, L.; Sen, K. K.; Schauder, C.D., "The interline power flow controller concept: a new approach to power flow management in transmission systems," IEEE Transactions on Power Delivery, Volume: 14 3 , July 1999, pp. 1115 –1123.

[E] Transient Modeling and Analysis

[E1] Gronquist, J. F.; Sethares, W. A.; Alvarado, F. L.; Lasseter, R.H., "Power oscillation damping control strategies for FACTS devices using locally measurable quantities," IEEE Transactions on Power Systems, Volume 10 3, Aug. 1995, pp. 1598 – 1605.

[E2] Reeve, J.; Lane-Smith, S. P.; Wikston, J. M., "Incorporation of FACTS into transients programs for system simulation," International Conference on AC and DC Power Transmission, 1991, pp. 379 – 383.

[E3] Galiana, F. D.; Almeida, K.; Toussaint, M.; Griffin, J.; Atanackovic, D.; Ooi, B. T.; McGillis, D. T., "Assessment and control of the impact of FACTS devices on power system performance," IEEE Transactions on Power Systems, Volume 11 4, Nov. 1996, pp. 1931 – 1936.

[E4] Lo, K. L.; Ma, T. T.; Trecat, J.; Crappe, M., "Detailed real-time simulation and performance analysis of UPFC using Electromagnetic Transients Program (EMTP)" Proceedings of 1998 International Conference on Power System Technology, POWERCON '98, pp. 889 - 894, Volume 2.

[E5] Gronquist, J.; Sethares, W.; Alvarado, F.; Lasseter, R., "Animated vectors for visualization of power system phenomena," Conference Proceedings on Power Industry Computer Application Conference, IEEE, 1995, pp. 121 – 127.

[E6] Pilotto, L.; Alves, J.; Watanabe, E., “High frequency eigenanalysis of HVDC and FACTS assisted power systems,” Proceedings IEEE Summer Power Meeting, Seattle, WA, July 2000.

[F] Transient Stability

[F1] Sadeghzadeh, S.M.; Ehsan, M.; Said, N. H.; Feuillet, R., “Improvement of transient stability limit in power system transmission lines using fuzzy control of FACTS devices,” 20th International Conference on Power Industry Computer Applications, 1997, pp. 331 –336.

[F2] Senjyu, T.; Molinas, M.; Uezato, K., “Multi-machine power system stabilization with FACTS equipment applying fuzzy control,” Proceedings of the 35th IEEE Conference on Decision and Control, 1996, pp. 2202 –2207 Volume 2.

[F3] Gjerde, J. O.; Flolo, R.; Gjengedal, T., “Use of HVDC and FACTS-components for enhancement of power system stability,” MELECON '96 8th Mediterranean Electrotechnical Conference, 1996. pp. 802 – 808, Volume 2.

[F4] Zakrzewski, R. R.; Kolodziej, W. J.; Mohler, R. R., “Application of hierarchical neural-network-based control to transient stabilization of interconnected power systems,” Proceedings of the 33rd IEEE Conference on Decision and Control, 1994, pp. 1883 –1884, Volume 2.

[F5] Pourbeik, P.; Gibbard, M. J., “Damping and synchronizing torques induced on generators by FACTS stabilizers in multimachine power systems,” IEEE Transactions on Power Systems, Volume 11 4, Nov. 1996, pp. 1920 –1925.

[F6] Fang, Y. J.; Macdonald, D. C., “Dynamic quadrature booster as an aid to system stability,” IEE Colloquium on Power System Dynamics Stabilization (Digest No. 1998/196 and 1998/278), 1998, pp. 11/1 - 11/7.

[F7] Overbye, T. J.; Brown, D., “Use of FACTS devices for power system stability enhancement,” Proceedings of the 36th Midwest Symposium on Circuits and Systems, 1993, pp. 1019 - 1022 Volume 2.

[F8] Ilić, M. D.; Xiaojun Liu; Chapman, J.W., “Control of the inter-area dynamics using FACTS technologies in large electric power systems,” Conference on Decision and Control, Proceedings of the 32nd IEEE, 1993, pp. 2370 - 2376 Volume 3.

[F9] Larsen, E.V.; Sanchez-Gasca, J. J.; Chow, J.H., “Concepts for design of FACTS controllers to damp power swings,” IEEE Transactions on Power Systems, Volume 10 2, May 1995, pp. 948 –956.

[F10] Zhao, J.; Ishigame, A.; Kawamoto, S.; Taniguchi, T., "Structural control of electric power networks for transient stability," IEEE Transactions on Power Systems, Volume 9 3, Aug. 1994, pp. 1575 –1581.

[F11] Arabi, S.; Kundur, P.; Hassink, P.; Matthews, D., "Small signal stability of a large power system as affected by new generation additions," Proceedings IEEE Summer Power Meeting, Seattle, WA, July 2000, paper 0-7803-6423-6/00.

[F12] Rivera, C.; Olguin, D.; Messina, A., "Analysis of subsynchronous torsional interactions with FACTS devices," Proceedings IEEE Summer Power Meeting, Seattle, WA, July 2000, paper 0-7000-6400-6/00.

[F13] Lee, S.; Seo, J.; Moon, S.; Park, J., "Observer-based decentralized optimal controller design of PSS and TCSC for enhancement of power system dynamic stability," Proceedings IEEE Summer Power Meeting, Seattle, WA, July 2000.

[F14] Praing, C.; Tran-Quoc, T.; Feuillet, R.; Sabonnadiěre, J.; Nicolas, J.; Nguyen-Boi, K.; Nguyen-Van, L., "Impact of FACTS devices on voltage and transient stability of a power system including long transmission lines," Proceedings IEEE Summer Power Meeting, Seattle, WA, July 2000, paper 0-7803-6403-6/00.

[F15] Perez, M.; Messina, A.; Fuerte-Esquivel, C., "Application of FACTS devices to improve steady state voltage stability," Proceedings IEEE Summer Power Meeting, Seattle, WA, July 2000, paper 0-7803-6423-6/00.

[G] Transient Specialized Control Structures

[G1] Senjyu, T.; Yamane, S.; Uezato, K., "Enhancement of power system stability with FACTS using adaptive fuzzy controller," IEEE International Conference on Systems, Man, and Cybernetics, 1999. IEEE SMC '99 Conference Proceedings. 1999, pp. 533 –538, Volume 6.

[G2] Jeongho Hong; Cummings, I. A.; Bernstein, D. S.; Washabaugh, P. D., "Stabilization of an electromagnetically controlled oscillator," Proceedings of the 1998 American Control Conference, 1998, pp. 2775 –2779, Volume 5.

[G3] Sadeghzadeh, S. M.; Ehsan, M.; Said, N. H.; Feuillet, R., "Improvement of transient stability limit in power system transmission lines using fuzzy control of FACTS devices," IEEE Transactions on Power Systems, Volume 13 3, Aug. 1998, pp. 917 – 922.

[G4] Pourbeik, P.; Gibbard, M. J., "Simultaneous coordination of power system stabilizers and FACTS device stabilizers in a multimachine power system for enhancing dynamic performance," IEEE Transactions on Power Systems, Volume 13 2, May 1998, pp. 473 – 479.

[G5] Wang, H. F., "Co-ordination of fixed-parameter robust damping controllers in multi-machine power systems," UKACC International Conference on Control '98 (Conference Publication No. 455), 1998, pp. 1140 - 1145, Volume 2.

[G6] Panciatici, P.; Daniel, D.; Nonnon, P.; Meyer, B., "User-defined equipment models for long term and transient stability studies," 2nd International Conference on Advances in Power System Control, Operation and Management, 1993. APSCOM- 93, 1993, pp. 878 - 883 Volume 2.

[G7] Lie, T. T.; Ghosh, A.; Shrestha, G. B., "Fuzzy logic control of power system transient stability," 2nd International Conference on Advances in Power System Control, Operation and Management, 1993. APSCOM- 93, 1993, pp. 515 - 520, Volume 2.

[G8] Carter, D. R.; Rodriguez, A. A., "Weighted H_∞ distributed parameter plants under sampled-data control," Proceedings of the 37th IEEE Conference on Decision and Control, 1998, pp. 313 - 318, Volume 1.

[G9] Fujita, G.; Yokoyama, R.; Niimura, T.; Makita, D.; Takeuchi, S.; Shirai, G., "Power system stabilizing control using variable series capacitor based on H_∞ control theory considering AVR and governor," IEEE Canadian Conference on Electrical and Computer Engineering, Engineering Innovation: Voyage of Discovery, 1997, pp. 43 –46.

[G10] Dilger, R.; Nelles, D., "Improvement of network damping and transient stability by active and reactive power control," IEE Proceedings - Generation, Transmission and Distribution, Volume 144 2, March 1997, pp. 125 –128.

[G11] Taranto, G. N.; Shiau, J.-K.; Chow, J. H.; Othman, H. A., "Robust decentralized design for multiple FACTS damping controllers," IEE Proceedings - Generation, Transmission and Distribution, Volume 144 1, Jan. 1997, pp. 61 –67.

[G12] Taranto, G. N.; Jaw-Kuen Shiau; Chow, J. H.; Othman, H. A., "A robust decentralized control design for damping controllers in FACTS applications," Applications Proceedings of the 4th IEEE Conference on Control, 1995, pp. 233 –238.

[G13] Rajkumar, V.; Mohler, R. R., "Nonlinear predictive control for the damping of multimachine power system transients using FACTS devices," Proceedings of the 33rd IEEE Conference on Decision and Control, 1994, pp. 4074 - 4079 Volume 4.

[G14] Mok, T.; Ni, Y.; Wu, F., "Design of fuzzy damping controller of UPFC through genetic algorithm," Proceedings IEEE Summer Power Meeting, Seattle, WA, July 2000.

[G15] Yang, Y.; Chen, H.; Wang, H.; Aggarwal, R.; Johns, A.; Dai, X.; Li, N., “Design and test of a TCSC ANN based α-th order inverse control system,” Proceedings IEEE Summer Power Meeting, Seattle, WA, Seattle, WA, July 2000.

[G16] Chen, H.; Zhou, R.; Wang, Y., “Analysis of voltage stability enhancement by robust nonlinear STATCOM control,” Proceedings IEEE Summer Power Meeting, Seattle, WA, Seattle, WA, July 2000.

[H] Device Applications And Placement (Transient)

[H1] Tavakoli Bina, M.; Hamill, D. C., “The bootstrap variable inductance: a new FACTS control element,” Annual IEEE Power Electronics Specialists Conference, 1999. PESC 99, pp. 619 – 625, Volume 2.

[H2] Guohong Wu; Yokoyama, A.; Jiali He; Yixin Yu, “Allocation and control of FACTS devices for steady-state stability enhancement of large-scale power system,” International Conference on Power System Technology, 1998. Proceedings POWERCON '98. pp. 357 –361, Volume 1.

[H3] Wang, H. F., “Selection of robust installing locations and feedback signals of FACTS-based stabilizers in multi-machine power systems,” IEEE Transactions on Power Systems, Volume 14 2, May 1999, pp. 569 –574.

[H4] Mehraban, A. S.; Edris, A.; Schauder, C. D.; Provanzana, J. H., “Installation, commissioning, and operation of the world's first UPFC on the AEP system,” 1998 International Conference on Power System Technology. Proceedings POWERCON '98. pp. 323 - 327 Volume 1.

[H5] Zhang, C.; Zhou, X. X.; Cao, Y. J.; Wu, Q. H., “Disturbances auto-rejection control of TCSC in power systems,” UKACC International Conference on Control '98. (Conference Publication No. 455), 1998, pp. 1017 - 1022, Volume 2.

[H6] Tso, S. K.; Ling, J.; Zen, Q.Y.; Loa, K.L.; Zhou, X. X., “Coordination of TCSC and SVC for stability improvement of power systems,” Fourth International Conference on Advances in Power System Control, Operation and Management, 1997. APSCOM- 97. (Conference Publication No. 450), pp. 371 - 376, Volume 1.

[H7] Christi, N.; Hedin, R.; Johnson, R.; Krause, P.; Montoya, A., “Power system studies and modeling for the Kayenta 230 kV substation advanced series compensation,” Proceedings of International Conference on AC and DC Power Transmission, 1991, pp. 33 – 37.

[H8] Xuan, Q. Y.; Johns, A. T.; Song, Y. H., "Adaptive protection technique for controllable series compensated EHV transmission systems using neural networks," 2nd International Conference on Advances in Power System Control, Operation and Management, APSCOM- 93, 1993, pp. 621 - 625, Volume 2.

[H9] Bina, M. T.; Hamill, D. C., "Harmonic analysis of the PWM series/parallel bootstrap variable inductance," Proceedings of the IEEE International Conference on Power Electronics and Drive Systems, 1999, PEDS '99, pp. 22 - 27, Volume 1.

[H10] Hamill, D.C.; Bina, M. T., "The bootstrap variable inductance and its applications in AC power systems." Fourteenth Annual Applied Power Electronics Conference and Exposition, APEC '99, Volume 2, 1999, pp. 896 - 802, Volume 2.

[H11] Li Chun; Jiang Qirong; Xie Xiaorong; Wang Zhonghong, "Rule-based control for STATCOM to increase power system stability," 1998 International Conference on Power System Technology, Proceedings. POWERCON '98. Volume 1, 1998, pp. 372 - 376, Volume 1.

[H12] Poshtan, M.; Rastgoufard, P., "Improvement of power system transient stability by using controllable series compensator," Proceedings of the Thirtieth Southeastern Symposium on System Theory, 1998, pp. 225 – 228.

[H13] Fang, Y. J.; Macdonald, D. C., "Dynamic quadrature booster as an aid to system stability," Generation, Transmission and Distribution, IEE Proceedings, Volume 145 1, Jan. 1998, pp. 41 –47.

[H14] Dong Shen; Yingduo Han; Zhonghong Wang; Retzmann, D.; Povh, D., "Real time digital simulation studies for SVC controller," International Conference on Power System Technology, 1998. Proceedings. POWERCON '98. 1998 Volume 1, 1998, pp. 406 - 410, Volume 1.

[H15] Ishida, F.; Taniguchi, H.; Egawa, M.; Fujita, H.; Konishi, H.; Watanabe, M., "Analogue simulation studies with actual controllers for TCSC," 1998 International Conference on Power System Technology, 1998. Proceedings. POWERCON '98., pp. 367 - 371, Volume 1.

[H16] Noroozian, M.; Angquist, L.; Ghandhari, M.; Andersson, G., "Improving power system dynamics by series-connected FACTS devices," IEEE Transactions on Power Delivery, Volume 12 4, Oct. 1997, pp. 1635 – 1641.

[H17] Cañizares, C.A.; Faur, Z.T., "Analysis of SVC and TCSC controllers in voltage collapse," IEEE Transactions on Power Systems, Volume 14 1, Feb. 1999, pp. 158 – 165.

[H18] Yang, N.; Liu, Q.; McCalley, J. D., "TCSC controller design for damping interarea oscillations," IEEE Transactions on Power Systems, Volume 13 4, Nov. 1998, pp. 1304 –1310

[H19] Peterson, H. R.; DeShazo, G. L.; Gerlach, D. W., "Application of static VAr compensators for the dynamic performance of the Mead-Adelanto and Mead-Phoenix," IEEE Transactions on Power Delivery Volume 10 1, Jan. 1995, pp. 459 – 466.

[H20] Patil, K. V.; Senthil, J.; Jiang, J.; Mathur, R. M., "Application of STATCOM for damping torsional oscillations in series compensated AC systems," IEEE Transactions on Energy Conversion, Volume 13 3, Sept. 1998, pp. 237 – 243.

[H21] Kang, Y.; Shrestha, G.; Lie, T., "Component level cascade control of UPFC," Proceedings IEEE Summer Power Meeting, Seattle, WA, Seattle, WA, July 2000.

[I] Coordinated Controls

[I1] Ngan, H.W.; Fang, W., "Coordinated power control strategy for flexible AC transmission system," Proceedings of the IEEE International Conference on Power Electronics and Drive Systems PEDS '99, 1999, pp. 677 - 682 Volume 2.

[I2] Sanchez-Gassy, J.J., "Coordinated control of two FACTS devices for damping interarea oscillations," IEEE Transactions on Power Systems, Volume 13 2, May 1998, pp. 428 – 434.

[I3] Yoke In Tan; Wang, Y., "Design of series and shunt FACTS controller using adaptive nonlinear coordinated design techniques," IEEE Transactions on Power Systems, Volume 12 3, Aug. 1997, pp. 1374 – 1379.

[I4] Khapalov, A.Y.; Mohler, R. R., "Global controllability of the power transmission network," Proceedings of the 35th IEEE Conference on Decision and Control, 1996, pp. 3400 - 3405 Volume 3.

[I5] Wang, Y.; Zhu, W.; Mohler, R. R.; Spee, R., "Variable-structure control of flexible AC transmission systems," Proceedings of the 31st IEEE Conference on Decision and Control, 1992, pp. 3544 –3 549 Volume 4.

[I6] Wang, H.; Wu, Q., "Multivariable design of a multiple-functional unified power flow controller," Proceedings IEEE Summer Power Meeting, Seattle, WA, Seattle, WA, July 2000.

[I7] Hingorani, N., "Role of FACTS in a deregulated market," Proceedings IEEE Summer Power Meeting, Seattle, WA, July 2000, paper 0-7803-6423-6/00.

[J] General References

[J1] Heydt G., Computer Analysis Methods for Power Systems, Stars in a Circle Publications, Scottsdale, AZ, 1995.

[J2] Wood A.; Wollenberg B., Power System Generation and Control, McGraw Hill, 1998.

[J3] Kunder, P.; Balu, N. J., Power System Stability and Control, EPRI Power System Engineering Series, Electric Power Research Institute, Palo Alto, CA, January 1998.

[J4] Lu, J.; Nehrir, M. H.; Pierre, D. A., "A fuzzy logic based adaptive power system stabilizer," IEEE Power Engineering Society 1999 Winter Meeting, pp. 92 –95, Volume 1.

[J5] Mohan, N., Power Electronics, John Wiley, New York, 1995.

[J6] Wu Chi-Jui; Hsu Yuan-Yih, "Design of self-tuning PID power system stabilizer for multimachine power systems," IEEE Transactions on Power Systems, Volume: 3 3 , Aug. 1988, pp. 1059 – 1064.

[J7] Hiskens, I.; Hill, D., "Incorporation of SVCs into energy function methods," IEEE Transactions on Power Systems, Feb. 1992, pp. 133-140.

[J8] North American Electric Reliability Council, "Available transfer capability definitions and determination," Princeton, NJ, June 1996, IEEE Summer Power Meeting, Vancouver BC, July 2001.

[J9] Lima, E.; Fernandes, L., "Assessing eigenvalue sensitivities," Proceedings IEEE Summer Power Meeting, Seattle, WA, July 2000, paper PE003PRS (05-99).

[J10] Maguire, T., "Real time digital electromagnetic transients simulation of power systems," Proceedings IEEE Summer Power Meeting, Seattle, WA, July 2000, paper 0-7803-6433-6/00.

[J11] Priest, J., "Economics of scale in transmission refurbishment and maintenance," Proceedings IEEE Summer Power Meeting, Seattle, WA, July 2000, panel session including discussion of FACTS devices, paper 0-7803-6403-6/00.

[J12] Seeley, K.; Lawarree, J.; Liu, C. C., "Analysis of electricity market rules and their effects on strategic behavior in a noncongestive grid," IEEE Transactions on Power Systems, Feb. 2000, pp. 157-162.

[J13] Gibescu M.; Liu, C. C., "Optimization of ancillary services for system security," Proceedings Bulk Power System Dynamics and Control IV – Restructuring, August 24-28, 1998, Santorini, Greece.

[J14] Edris, A. “FACTS technology development: an update,” IEEE Power Engineering Review, Vol. 20, No. 3, March 2000, pp. 4 – 9.

[J15] Bose, B., “Energy, environment, and advances in power electronics,” IEEE Transactions on Power Electronics, Vol. 15, No. 4, July, 2000, pp. 688 – 701.

[J16] Liu, C. C.; Heydt, G. T.; Edris, A., “Critical system strategies for FACTS control logic,” Proceedings of the IEEE 2001 Summer Power Meeting, Vancouver, BC, Canada, July, 2001

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