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Utilization of FACTS devices for improving the Operation of an Electrical Power System

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ABSTRACT
Inthelasttwodecades,powerdemandhasincreasedsubstantiallywhiletheexpansionofpowergenerationandtransmissionhasbeenseverelylimitedduetolimitedresourcesandenvironmentalrestrictions.Asaconsequence,some transmission lines are heavily loaded and thesystem stability becomes a power transfer-limitingfactor. Flexible AC transmission systems (FACTS)controllershavebeenmainlyusedforsolvingvariouspowersystemsteadystatecontrolproblems.FlexibleACtransmissionsystemsorFACTS are devices which allow the flexible anddynamic control of power systems.Enhancementof system stability using FACTS controllers hasbeen investigated. This paper is aimed towards thebenefitsofutilizingFACTSdeviceswiththepurposeofimprovingtheoperationofanelectrical power system. Performance comparisonof different FACTS controllers has been discussed.Inaddition,someoftheutilityexperienceandsemiconductor technology development have beenreviewedandsummarized.ApplicationsofFACTS to power system studies have also beendiscussed.

I. INTRODUCTION

TheFACTScontrollersofferagreatopportunitytoregulatethetransmissionofalternatingcurrent(AC),increasingordiminishingthepowerflowinspecificlinesandrespondingalmostinstantaneouslytothestability problems. The potential of this technology isbasedonthepossibilityofcontrollingtherouteofthepowerflowandtheabilityofconnectingnetworksthatarenotadequatelyinterconnected,givingthepossibility of trading energy between distant agents.FlexibleAlternatingCurrentTransmissionSystem(FACTS)isastaticequipmentusedfortheACtransmissionofelectricalenergy.Itismeanttoenhance controllability and increase power transfercapability.Itisgenerallyapower electronicsbaseddevice.

The FACTS devices can be divided in three groups,dependentontheirswitchingtechnology:mechanicallyswitched(suchasphaseshiftingtransformers), thyristorswitchedorfastswitched,using IGBTs. While some types of FACTS, such asthe phase shifting transformer (PST) and the staticVAR compensator (SVC) are already well known andused in power systems, new developments in powerelectronics and control have extended the applicationrangeofFACTS.Furthermore,intermittentrenewableenergysourcesandincreasinginternational power flows provide new applicationsforFACTS.TheadditionalflexibilityandcontrollabilityofFACTSallowtomitigatetheproblems associatedwiththeunreliableofsupplyissues of renewable. SVCs and STATCOM devicesare well suited to provide ancillary services (such asvoltagecontrol)tothegridandfaultridthroughcapabilitieswhichstandardwindfarmscannotprovide Furthermore, FACTS reduce oscillations inthe grid, which is especially interesting when dealingwiththestochasticbehaviorof renewable.

1. CONTROLOFPOWERSYSTEMS

Generation,Transmission,Distribution

In any power system, the creation, transmission, andutilization of electrical power can be separated intothree areas, which traditionally determined the way inwhichelectricutilitycompanieshad beenorganized.

Theseareillustratedin Figure1andare:

- Generation
- Transmission
- Distribution

Fig–1Blockdiagramofgeneration,transmission&distribution

Althoughpowerelectronicbasedequipmentisprevalent in each of these three areas, such as withstatic excitation systems for generators and

CustomPowerequipmentindistributionsystems[8],the focus of this paper and accompanying presentation ison transmission, i.e, moving the power from where itisgeneratedtowhereitisutilized.

PowerSystemConstraints

As notedin the introduction, transmissionsystemsare being pushed closer to their stability and thermallimitswhilethefocusonthequalityofpowerdelivered is greater than ever. The limitations of thetransmission system can take many forms and mayinvolvepowertransferbetweenareasorwithinasingle area or region and may include one or more ofthefollowingcharacteristics:

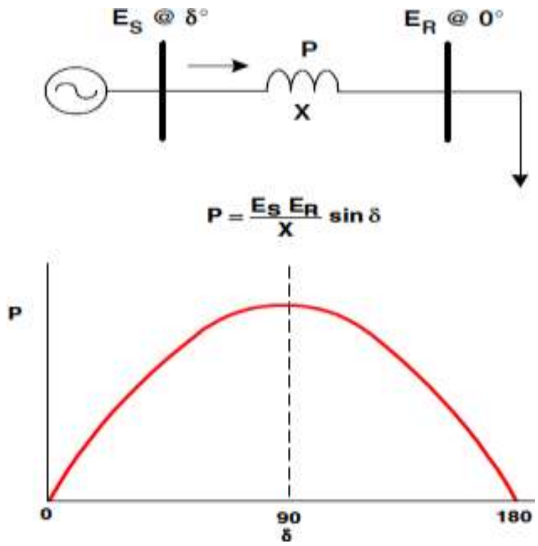
- Steady-StatePowerTransferLimit
- VoltageStabilityLimit
- DynamicVoltageLimit
- TransientStabilityLimit
- PowerSystemOscillationDampingLimit
- InadvertentLoopFlowLimit
- ThermalLimit
- Short-CircuitCurrentLimit
- Others

Each transmission bottleneck or regional constraintmayhaveoneormoreofthesesystem-levelproblems. The key to solving these problems in themostcost-effectiveandcoordinatedmannerisbythoroughsystems engineeringanalysis.

ControllabilityofPowerSystems

To illustrate that the power system only has certainvariables that can be impacted by control, we haveconsideredherethepower-anglecurve,showninFigure 2. Although this is a steady-state curve and theimplementation of FACTS is primarily for dynamicissues,thisillustrationdemonstratesthepointthatthere are primarily three main variables that can bedirectly controlled in the power system to impact itsperformance.These are:

- Voltage
- Angle
- Impedance



Fig–2.Illustrationofcontrollabilityofpowersystems

Wecanalsoinferthepointthatdirectcontrolof power is a fourth variable of controllability in powersystems. With the establishment of “what” variablescanbecontrolledinapowersystem,thenextquestion is “how” these variables can be controlled.Theanswerispresentedintwoparts:namely conventionalequipmentandFACTScontrollers.

Examples of Conventional Equipment ForEnhancingPower SystemControl

- SeriesCapacitor -Controlsimpedance
- Switched Shunt-Capacitor and Reactor -Controls voltage
- TransformerLTC-Controlsvoltage
- PhaseShiftingTransformer-Controlsangle
- SynchronousCondenser-Controlsvoltage
- SpecialStabilityControls-Focusesonvoltagecontrolbutoftenincludedirect controlofpower
- Others (When Thermal Limits are Involved) -Canincludedreconductoring,raisingconductors, dynamiclinemonitoring,addingnewlines, etc.

ExampleofFACTSControllersforEnhancingPowerSystemControl

- StaticSynchronousCompensator(STATCOM) -Controlsvoltage
- StaticVARCompensator(SVC)-Controlsvoltage
- UnifiedPowerFlowController(UPFC)
- ConvertibleSeriesCompensator(CSC)
- Inter-phasePowerFlowController(IPFC)
- StaticSynchronousSeriesController(SSSC)

Each of the above mentioned controllers haveimpact on voltage, impedance, and/or angle (andpower)

- ThyristorControlledSeriesCompensator(TCSC) -Controlsimpedance

- ThyristorControlledPhaseShiftingTransformer(TCPST)-Controlsangle
- SuperConductingMagneticEnergyStorage(SMES)-Controls voltageand power

BenefitsofControlofPowerSystems
Oncepowersystemconstraintsareidentifiedandthrough system studies viable solutions options areidentified,thebenefitsof theaddedpowersystemcontrolmustbedetermined.The following offers alistofsuchbenefits:
- IncreasedLoadingandMoreEffectiveUseofTransmission Corridors
- AddedPowerFlowControl
- ImprovedPowerSystemStability
- IncreasedSystemSecurity
- IncreasedSystemReliability
- Added FlexibilityinStartingNewGeneration
- EliminationorDeferraloftheNeedforNewTransmission Lines

Benefitsofutilizing FACTSdevices
The benefits of utilizing FACTS devices in electricaltransmission systems can be summarized as follows[1]:
- Betterutilizationofexistingtransmissionsystemassets
- Increased transmission system reliability andavailability
- Increaseddynamicandtransientgridstabilityandreductionofloopflows
- Increasedqualityofsupplyforsensitiveindustries
- EnvironmentalbenefitsBetterutilizationofexistingtransmission systemassets

Classification
TherearedifferentclassificationsfortheFACTSdevices:
DependingonthetypeofconnectiontothenetworkFACTSdevicescandifferentiatefourcategories
- serialcontrollers
- derivationcontrollers
- serialtoserialcontrollers
- serial-derivationcontrollers

Dependingontechnologicalfeatures,theFACTSdevicescanbe divided into twogenerations
- firstgeneration:usedthyristorswithignitioncontrolledbygate(SCR).
- second generation: semiconductors with ignitionandextinctioncontrolledbygate(GTO´s, MCTS, IGBTS,IGCTS, etc).

Thesetwoclassificationsareindependent,existingforexample,devicesofagroupofthefirstclassification that can belong to various groups of thesecond classification. The main difference betweenfirst and second generation devices is the capacity togeneratereactivepowerandtointerchangeactivepower.

ThefirstgenerationFACTSdevicesworklike passiveelementsusingimpedanceortapchangertransformerscontrolledbythyristors.Thesecondgeneration FACTSdevicesworklikeangleandmodulecontrolled voltagesourcesandwithoutinertia,basedinconverters, employingelectronictension sources(three-phase inverters, auto-switchedvoltage sources, synchronous voltage sources, voltagesource control) fast proportioned and controllable andstaticsynchronousvoltageand currentsources.

2. FIRSTGENERATIONOFFACTS

StaticVARCompensator(SVC)
A static VAR compensator (or SVC) is an electricaldeviceforprovidingfast-actingreactivepoweronhigh-voltage electricity transmission networks. SVCsarepartoftheFlexibleACtransmissionsystemdevice family, regulating voltage and stabilising thesystem. The term "static" refers to the fact that theSVC has no moving parts (other than circuit breakersand disconnects, which do not move under normalSVC operation). Prior to the invention of the SVC,power factor compensation was the preserve of largerotating machines such as synchronous condensers.TheSVCisanautomatedimpedancematchingdevice, designed to bring the system closer to unitypower factor. If the power system's reactive load iscapacitive(leading),theSVCwillusereactors(usuallyintheformofThyristor-ControlledReactors)toconsumeVARsfromthesystem,loweringthesystemvoltage.Underinductive(lagging)conditions,thecapacitorbanksareautomaticallyswitchedin,thusprovidingahighersystem voltage. They also may be placed near highandrapidlyvaryingloads,suchasarcfurnaces,where they can smooth flicker voltage.It is knownthat the SVCs with an auxiliary injection of a suitablesignal can considerably improve the dynamic stabilityperformance of a power system . It is observed thatSVCcontrolscansignificantlyinfluencenonlinear systembehaviorespeciallyunderhigh-stressoperatingconditionsandincreased SVC gains.

Thyristor-Controlled Series Capacitor (TCSC)TCSCcontrollersusethyristor-controlledreactor(TCR) in parallel with capacitor segments of seriescapacitorbank.ThecombinationofTCRandcapa citorallowthecapacitivereactancetobesmoothly controlled over a wide range and switcheduponcommandtoaconditionwherethebi-directional thyristor pairs conduct continuously andinsertaninductive reactanceinto the line.

TCSCisaneffectiveandeconomicalmeansofsolvingproblemsoftransientstability,dynamicstability, steady state stability and voltage stability inlong transmission lines. TCSC, the first generation ofFACTS, can control the line impedance through theintroductionofathyristorcontrolledcapacitorinseries with the transmission line. A TCSC is a seriescontrolledcapacitivereactancethatcanprovidecontinuous control of poweron the ac line over awiderange.ThefunctioningofTCSCcanbecomprehendedbyanalyzingthebehaviorofavariableinductorconnectedinserieswithafixedcapacitor

Thyristor-ControlledPhaseShifter(TCPS)
In a TCPS control technique the phase shift angle isdetermined as a nonlinear function of rotor angle andspeed.However,inreal-lifepowersystemwithalarge number of generators, the rotor angle of a singlegeneratormeasuredwithrespecttothesystemreferencewillnotbeverymeaningful.

3. SECONDGENERATIONOFFACTS
StaticCompensator(STATCOM)

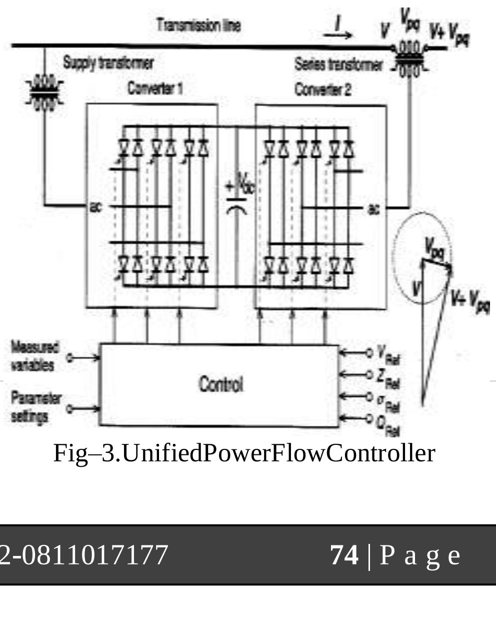
The emergence of FACTS devices and in particularGTOthyristor-basedSTATCOMhasenabledsuchtechnologytobeproposedasseriouscompetitivealternativestoconventionalSVC[21]Astaticsynchronouscompensator(STATCOM)isaregulatingdeviceusedonalternatingcurrent electricitytransmissionnetworks.Itisbasedonapower electronics voltage-source converter and canact as either a source or sink of reactive AC power toan electricity network. If connected to a source ofpower it can also provide active AC power. It is amember of the FACTS family of devices. Usually aSTATCOMisinstalledtosupportelectricitynetworks thathaveapoorpowerfactorandoftenpoorvoltageregulation.Therearehowever,otheruses,themostcommon useisforvoltagestability.
From the power system dynamic stability viewpoint,theSTATCOMprovidesbetterdampingcharacteristics than the SVC as it is able to transientlyexchangeactivepowerwiththesystem.

StaticSynchronousSeriesCompensator(SSSC)

This device work the same way as the STATCOM. Ithas a voltage source converter serially connected to atransmissionlinethroughatransformer.Itisnecessary an energy source to provide a continuousvoltage through a condenser and to compensate thelosses of the VSC. A SSSC is able to exchange activeand reactive power with the transmission system. Butif our only aim is to balance the reactive power, theenergysourcecouldbequitesmall.Theinjectedvoltage can be controlled in phase and magnitude ifwe have an energy source that is big enough for thepurpose. With reactive power compensation only thevoltageiscontrollable,becausethevoltagevectorforms 90º degrees with the line intensity. In this casethe serial injected voltage can delay or advanced thelinecurrent.ThismeansthattheSSSCcanbeuniformlycontrolledinanyvalue,intheVSCworkingslot.

UnifiedPowerFlow Controller(UPFC)

A unified power flow controller (UPFC) is the mostpromising device in the FACTS concept. It has theability to adjust the three control parameters, i.e. thebus voltage, transmission line reactance, and phaseanglebetweentwobuses,eithersimultaneouslyorindependently.AUPFCperformsthisthroughthecontrol of the in-phase voltage, quadrature voltage,andshuntcompensation.TheUPFCisthemost versatileandcomplexpowerelectronicequipmentthat has emerged for the control and optimization ofpower flow in electrical power transmission systems.It offers major potential advantages for the static anddynamic operation of transmission lines. The UPFCwas devised for the real-time control and dynamiccompensation of ac transmission systems, providingmultifunctional flexibility required to solve many ofthe problems facing the power industry. Within theframeworkoftraditionalpowertransmissionconcepts, the UPFC is able to control, simultaneouslyor selectively, all the parameters affecting power flowinthetransmissionline.Alternatively,itcanindependentlycontrolboththerealandreactivepowerflowinthelineunlikeallothercontrollers.



Fig–3.UnifiedPowerFlowController

4. TYPESOFNETWORK CONNECTION

Serialcontrollers.

It can consist of a variable impedance as a condenser,coil, etc or a variable electronics based source at afundamental frequency. The principle of operation ofall serial controllers is to inject a serial tension to theline. Avariable impedance multiplied by the currentthatflowsthroughitrepresentstheserialtension.Whilethetensionisinquadraturewiththelinecurrent the serial controller only consumes reactivepower; any other phase angle represents managementofactivepower.AtypicalcontrollerisSerialSynchronousStaticCompensator(SSSC).

Controllersinderivation.

As it happens with the serial controller, the controllerinderivationcanconsistofavariableimpedance,variablesourceoracombinationofboth.Theoperationprincipleofallcontrollersinderivationistoinjectcurrenttothesysteminthepointofconnection. A variable impedance connected to theline tension causes variable current flow, representingan injection of current to the line. While the injectedcurrentisinquadraturewiththelinetension,the controllerinderivationonlyconsumesreactivepower; any other phase angle represents managementof active power. A typical controller is SynchronousStaticCompensator (STATCOM).

Serial-serialControllers.

Thistypeofcontrollerscanbeacombinationofcoordinatedserialcontrollersinamultilinetransmissionsystem.Orcanalsobeanunifiedcontrollerinwhichtheserialcontrollersprovideserialreactivecompensationforeachlinealsotransferring active power between lines through thelinkofpower.Theactivepowertransmissioncapacity,thatpresenta unifiedserial controllerorlinefeed power controller, makes possible the active andreactive power flow balance and makes theuse oftransmission bigger. In this case, the term “unified”means that the DC terminals of the converters of allthe controllers are connected to achieve a transfer ofactive power between each other. A typical controlleristheInterlinePowerFlowCompensator(IPFC).

Serial-derivationControllers.

Thisdevicecanbeacombinationofserialandderivationscontrollersseparated,coordinatelycontrollledor aunifiedpowerflow controllerwithserialandderivationelements.Theprincipleofoperationoftheserial-derivationcontrollersistoinject current to the system through the component inderivation of the controller, andserial tensionwiththelineutilizingtheserialcomponent.Whenthe

serial and derivation controllers are unified, they canhaveanexchangeofactivepowerbetweenthemthroughtheirlink.AtypicalcontrollerisUnifiedPower Flow Controller (UPFC), which incorporatingfunction of a filtering andconditioning becomes aUniversalPowerLineConditioner (UPLC).

5. FACTSAPPLICATIONSTOSTEADYSTATEPOWERSYSTEMPROBLEMS

For the sake of completeness of this review, a briefoverviewoftheFACTSdevicesapplicationstodifferentsteadystatepowersystemproblemsispresented in this section. Specifically, applications ofFACTSinoptimalpowerflowandderegulatedelectricitymarketwillbe reviewed.

FACTS Applications to Optimal Power Flow Inthelasttwodecades,researchersdevelopednewalgorithmsforsolvingtheoptimalpowerflowproblemincorporatingvariousFACTSdevices[11].GenerallyinpowerflowstudiesthethyristorcontrolledFACTSdevices,suchasSVCandTCSC,areusuallymodeledascontrollableimpedance[4,9,10,12-14].However,VSC-basedFACTSdevices,includingIPFCandSSSC,shuntdeviceslikeSTATCOM,andcombineddeviceslikeUPFC,aremorecomplexandusuallymodeledascontrollablesources[4,9,13-17,20].TheInterlinePowerFlowController(IPFC)isoneofthevoltagesourceconverter(VSC)basedFACTSControllerswhichcaneffectivelymanagethepowerflowviamulti-lineTransmissionSystem.

FACTS Applications to DeregulatedElectricity Market

Nowadays, electricity demand is rapidly increasingwithoutmajorreinforcementprojectstoenhance powertransmissionnetworks.Also,theelectricitymarket is going toward open market and deregulationcreating an environment for forces of competition andbargaining. FACTS devices can be an alternative toreduce the flows in heavily loaded lines, resulting inan increased load ability, low system loss, improvedstability of the network, reduced cost of production,and fulfilled contractual requirements by controllingthepowerflowsinthenetwork.Generally,thechanging nature of the electricity supply industry isintroducingmanynewsubjectsintopowersystemoperationrelatedtotradinginaderegulatedcompetitivemarket.Commercialpressuresonobtaininggreaterreturnsfromexistingassetssuggests an increasingly important role for dynamicnetworkmanagementusingFACTSdevicesandenergystorageasanimportantresourceingeneration, transmission, distribution, and customerservice.Therehasbeenanincreaseduseofthe FACTS devices applications in an electricity markethavingpoolandcontractual dispatches.

6. APPLICATIONS AND TECHNICALBENEFITSOFFACTS

The technical benefits of the principal for dynamicapplicationsofFACTSinaddressingproblemsintransientstability,dampening,postcontingencyvoltage control and voltage stability are summarizedin Table-1. FACTS devices are required when there isa need to respond to dynamic (fast-changing) networkconditions. The conventional solutions are normallyless expensive than FACTS devices, but limited intheirdynamicbehavior.Itisthetaskoftheplannerstoidentifythemosteconomicsolution.

	Load Flow Control	Voltage Control	Transient Stability	Dynamic Stability
SVC	●	●●●	●	●●
STATCOM	●	●●●	●●	●●
TCSC	●●	●	●●●	●●
UPFC	●●●	●●●	●●	●●

● ●● ●●● Better

Table1.TechnicalbenefitsofthemainFACTSdevices

II. CONCLUSION

The essential features of FACTS controllers and theirpotentialtoimprovesystemstabilityistheprimeconcern for effective & economic operation of thepowersystem.Thelocationandfeedbacksignalsused for design of FACTS-based damping controllerswerediscussed.Thecoordinationproblemamong differentcontrolschemeswasalsoconsidered.PerformancecomparisonofdifferentFACTScontrollershasbeenreviewed.Thelikelyfuturedirection ofFACTStechnology,wasdiscussed.Inaddition,utilityexperienceandmajorreal-worldinstallationsandsemiconductortechnologydevelopment have been summarized. A brief reviewof FACTS applications to optimal power flow andderegulatedelectricity markethasbeenpresented.

REFERENCES

[1] Y. N. Yu, Electric Power System Dynamics.AcademicPress, 1983.
[2] P. W. Sauer and M. A. Pai, Power SystemDynamicsandStability.PrenticeHall,1998.
[3] J.R.Smith,G.Andersson,andC.W.Taylor, “Annotated Bibliography on PowerSystemStabilityControls:1986-1994”,IEEETrans.onPWRS,11(2)(1996),pp. 794–800.
[4] N.G.HingoraniandL.Gyugyi,UnderstandingFACTS:ConceptsandTechnologyofFlexibleACTransmissionSystems.NewYork:IEEEPress,2000.
[5] N.G.Hingorani,“FACTS-FlexibleACTransmissionSystem”,Proceedings of 5thInternationalConferenceonACandDCPowerTransmission-IEEConferencePublication 345,1991,pp.1–7.
[6] N.G.Hingorani,“FlexibleACTransmission”, IEEE Spectrum, April 1993,pp.40–45.
[7] N. G. Hingorani, “High Power ElectronicsandFlexibleACTransmissionSystem”,IEEEPowerEngineeringReview,July1988
[8] R. M. Mathur and R. S. Basati, Thyristor-BasedFACTSControllersforElectricalTransmission Systems. IEEE Press Series inPower Engineering, 2002.
[9] Yong Hua Song and Allan T. Johns, FlexibleACTransmissionSystems(FACTS).London,UK: IEE Press,1999.
[10] M.NoroozianandG.Andersson,“PowerFlowControlbyUseofControllableSeriesComponents”, IEEE Trans. PWRD,8(3)(1993),pp.1420–1429.
[11] M.A.Abdel-MoamenandN.P.Padhy,“Optimal Power Flow Incorporating FACTSDevicesBibliographyandSurvey”,IEEEPESTransmissionandDistributionConference and Exposition, 7–12 September2003,vol. 2,pp. 669–676.
[12] E.Acha,C.R.Fuerte-Esquivel,andH.Ambriz-Perez,“AdvancedSVCmodelforNewton-RaphsonLoadFlowandNewtonOptimal Power Flow Studies”, IEEE Trans.PWRS, **15**(**1**)(2000), pp.129–136.
[13] E.Acha,C.R.Fuerte-Esquivel,andH.Ambriz-Perez et al., FACTS: Modeling

andSimulationinPowerNetworks,London,U. K.:Wiley, 2004.

[14] D. J. Gotham and G. T. Heydt, “Power FlowControlandPowerFlowStudiesforSystemswithFACTSDevices”,IEEETrans.PWRS, **13**(**1**)(1998),pp. 60–65.

[15] L. Gyugyi, K. K. Sen, and C. D. Schauder,“TheInterlinePowerFlowControllerConcept: a New Approach to Power FlowManagementinTransmissionSystems”,IEEE Trans. PWRD, 14(3)(1999), pp. 1115–1123.

[16] T.S.Chung,D.Qifeng,Z.Bomina,“Optimal Active OPF with FACTS Devicesby Innovative Load-Equivalent Approach”,IEEEPowerEngineeringReview,**20**(**5**)(2000),pp.63–66.

[17] YingXiao,Y.H.Song,andY.Z.Sun,“PowerFlowControlApproachtoPowerSystems With Embedded FACTS Devices”,IEEETrans.onPWRS,17(4)(2002), pp.943–950

[18] X. Dai, J. Liu, Y. Tang, N. Li, and H. Chen,“Neural Network αth-Order Inverse ControlofThyristorControlledSeriesCompensator”,ElectricPowerSystemsResearch, 45(1998), pp. 19–27.

[19] T.Senjyu,S.Yamane,Y.Morishima,K.Uezato, andH.Fujita,“ImprovementofMultimachine Power System Stability withVariableSeriesCapacitorUsingOn-LineLearningNeuralNetwork”,Int.J.Electrical Power& EnergySystems,25(3)(2003), pp.403–409.

[20] A. Nabavi-Niaki and M. R. Iravani, “Steady-State and Dynamic Models of Unified PowerFlow Controller (UPFC) for Power SystemStudies”,IEEETransactionsonPowerSystems, 11(4)(1996),pp. 1937–1943.

[21] D. J. Hanson, M. L. Woodhouse,C.Horwill, D.R.Monkhouse,andM.M.Osborne,“STATCOM:ANewEraofReactiveCompensation”,PowerEngineeringJournal,June 2002, pp.151–160.