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Designing and Modeling of Sliding Mode Controller for Multi-Area Multi-Source Interconnected AGC system using TLBO Optimization Technique

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ABSTRACT
Thispaperrepresentsdesignofoutputfeedbackslidingmodecontroller(SMC)formultiareamulti-source interconnected power system. After designing output feedback SMC, teaching and learningbased optimization (TLBO) technique is utilized to optimize feedback gain and switching vector of thecontroller.Thesuperiorityoftheproposedapproachisshownbycomparingtheresultwithoutputfeed-back tuned SMC with differential evolution and particle swarm optimization and state feedback SMCtunedwithgeneticalgorithmforatwoareathermalinterconnectedpowersystem.Further,theproposedapproach is extended to multi-area multi-source non linear automatic generation control (AGC) systemwith/withoutHVDClink.Firstareaconsistsupthermal,hydroandgas;secondareaconsists upthermal,hydro and nuclear as generating unit. Additionally, the superiority of proposed approach is shown by sen-sitivityanalysis,whichiscarriedoutwithwidechangesinsystemparameters.

INTRODUCTION

Large scale power systems are operated as interconnected sys-tem. The purpose of the interconnected power system is to gener-ate,exchangeandcontrolofelectricalenergywith nominalfrequencyandterminalvoltage.Thenominalsystemfrequencydepends on generated and consumed real power [1]. At normalstate nominal system frequency changes, when instantaneous loaddemand exceeds than generated power. In order to maintain fre-quency balance in power system, synchronous generator sensesthefrequencydeviationandchangesitsgeneration amount.Hence,theconceptofautomaticgenerationcontrol(AGC)comesin study. Practically power systems are normally composed of con-trol areas or regions representing coherent groups of generators.Thecontrolareamayhavethecombination of thermal, hydro,gas,nuclear, renewableenergy sources, etc. [2].

However, owingtotheirhighefficiency,nuclearplantsareusuallykeptatbaseload.Gaspowergenerationisidealformeetingthevaryingloaddemandand are normally used to meet peak demands. Keeping in view thepresentpowerscenario,combinationofmulti-sourcegeneratorsinacontrolareawiththeircorrespondingparticipationfactorsismorerealisticforthestudyofAGC.

Manyresearchersaretryingtoproposeseveralstrategiesfor AGC of power systems in order to maintain the system frequencyandtieline flow attheirscheduled valuesduringnormaloperationand also during small perturbations. Recent philosophies and con-trolstrategiesofAGChasbeenpresented.

Fromlit-erature survey, it is found that earlier different methodology andintelligent techniques have been proposed for better AGC systemsbasedonmodernoptimalcontrol[4,5],fuzzylogicbasedgainscheduling [6,7], neural network [8], reinforced learning algorithm[9],adoptiveneuro-fuzzyinterfacesystem(ANFIS)[10],PSObasedapplication with fuzzy system [11], bacterial forging optimizationalgorithm (BFOA) optimized several classical controller [12], frac-tionalorderproportionalintegralderivative(PID) controller[13].

Each controller has its own advantages and disadvantages, suchas linear optimal controller is sensitive to variation in the plantparametersandoperating condition of power systems. Trainingofanartificialneuralnetwork(ANN)and

ANFISisamajorexercise,because it depends on various factors such as the availability ofsufficient and accurate training data, suitable training algorithm,numberofneuronsintheANN,number ofANNlayers.Designofa fuzzy based controller requires more design decision than usual,for example, regarding the number of membership functions, theirshape, and their overlap for all inputs and outputs, rule base, infer-enceengine,defuzzification,anddatapreandpost processing.Therefore, ANN, ANFIS and fuzzy logic based controllers suffersfrom the requirement of expert user in their design and implemen-tation, and mathematical rigors and so are sensitive to the experts'depthofknowledgeinproblemdefinition.

We can see thatslidingmodecontroller(SMC)is adopted for AGC system, which shows good transient response and robustnessofcontrollercomparedtoconventional controller. Fordesigningof

SMCfeedbackgainsandswitchingvectorsshould beselectedprop-erly. In [19]Genetic algorithm (GA) and in [20]particle swarmoptimization (PSO) technique is used to optimize only feedbackgains of SMC for single area non-reheat thermal system. The opti-mal designing of whole SMC i.e. both feedback gains and switchingvectors are optimized using GA for two same area interconnectednon-reheat thermal system in[21].Tooptimized SMC the authorin[21]consideredlinearstatefeedbackcont rol,practicallytoaccess all state variables of a power system is limited and not fea-sible to measurement all of them and also costly [22,23]. To over-cometheproblemoptimaloutputfeedbackcontrol lerisconsideredin[22,23].
From literature survey, it is also noticed that many researchersadopted thermal-thermal or hydro-thermal systems for AGC stud-ies.Afewresearchersconsideredrealisticpowers ystemwithmulti-sourcegenerations.In[23],theauthorconsidereds ingleareathermal-hydro-gassystemwithoptimaloutputfeedbackcon-troller. In [24], the author considered differential evolution (DE)tunedPIDcontrollerperformsbetterthanopti maloutputfeedbackcontroller[22]fortwosamear eaofthermal-hydro-gaswithAC-DClinkconnectedparalleltoAC-tieline.In[25],authorproposedteaching learning based optimization (TLBO) algorithm tuned PIDcontroller performs better than DE tuned PID controller [24]andoptimal output feedback controller [22]for the same system. Inthat paper, author claimed that TLBO algorithm is simple in con-cept,easyimplementationandshowsrobustnessf orrealisticpowersystem.
Thispaperproposesdesignofoptimaloutputfeedb ackofwhole SMC for multi area multi-source nonlinear AGC system using TLBOalgorithm. Initially, SMC with output feedback is considered for atwoareasthermalAGCsystemandTLBOalgorit hmisemployedto tune switching vector and feedback gains of SMC. The superior-ity of proposed approach is illustrated by comparing the dynamicperformances of the system with state feedback SMC tuned usingGA[21].Finally,theproposedapproachisex tendedtounequal areasofsixdifferentgeneratingunitsofnon-linearAGCsystems

in pu Hz; T_{G1} and T_{G2} are the speed governor time constants insec;DP_{V1}andDP_{V2}arethechangeingovernor valve positions(pu); DP_{G1} and DP_{G2} are the governor output command (pu); $T_{T1}$and T_{T2} are the turbine time constant in sec; DP_{T1} and DP_{T2} arethe change in turbine output powers; DP_{D1} and DP_{D2} are the loaddemand changes; $DP_{Tie}$is the incremental change in tie line power(pu); K_{PS1} and K_{PS2} are the power system gains; T_{PS1} and T_{PS2} are thepower system time constant in sec; T_{12} is the synchronizing coef-ficientandDf_1andDf_2arethesystemfrequency deviations inHz. A typical value of 0.015 pu/s is considered as generation rateconstraint(GRC).

OverviewofSMCandTLBOalgorithm
TheoryofSMC

Fundamental theory of SMC is considered form book [27]. ThesimplifieddiagramofSMCisgiveninFig.2,w herethecontrollawisoutputfeedbackcontrol[22]. Theinterconnectedpowersys-temconsideredforstudycanberepresentedas

$$X = AX + BU \quad (1)$$

$$y = CX \quad (2)$$

whereX is n-dimensional state vector, U is m-dimensional controlforcevector,Aisa[n × n]systemmatrix,andBis[n × m]inputmatrix.Yisak-dimensionaloutputvector. C is [k × n] matrix. InthispaperDf$_1$,Df$_2$,ACE$_1$andACE$_2$isconsidered asoutputfeedback states.

TheSMCcontrollawofthegivensystemaregiven by
n
uі¼—wіy¼— wіjyj ð3Þ
i¼1
wherethefeedbackgainsaregivenby

withAC-DClink connectedparallel withexistingAC tie-line,where firstareathermal-hydro-gasgeneratingunitsareconsideredandinsecondareathermal-hydro-nucleargeneratingunitsareassumed
wіj
aij; ifyjrі>0; wherei¼1;2;…;m 4
—aij;ifyjrі<0;wherej¼1;2; ;k

withappropriategenerationrateconstraint(GRC) ineacharea.
Themainaimofpresentwork

(i) Toproposeoptimaldesignofoutputfeedbackof SMC.
(ii) TLBO algorithm is employed to tune switching vector andfeedback gain of SMC. Dynamic performances of a two areathermal AGC system are compared to output feedback SMCtuned with PSO, DE technique and with state feedback ofSMCusingGA[21].
(iii) Then, extended to interconnected multi area multi-sourcenonlinear AGC system with HVDC link. Thermal-hydro-gasgeneratingunitsareconsideredasfirstareaandthermal-hydro-nuclear generating units areconsidered assecondareawithappropriateGRC.
(iv) Simulations results are presented to show the effectivenessoftheproposedcontrollerconsideringtwoobjective
And
rіðyÞ¼S^{T}y¼0;wherei¼1;2;…;m ð5Þ

whereS$_i$aretheswitchingvectors.

Objectivefunction

While designing a controller objective function is first consid-ered based on specification and constrained. Four kind of perfor-mancecriteriagenerallyconsideredincontrol design approachare integral square error (ISE), integral time absolute error (ITAE),integral time square error (ITSE) and integral of absolute error(IAE).In[21],authorconsideredamodifiedobjectivefunctiongiven by Eq. (6) and proves to be better objective function. In thispaper, the same objective function given by Eq. (6)is consideredforpropercomparisonofcontrollerstructureandtechnique.

functions. jDtiej ðÞ
Z
J t05 f t f
075t P 6

¼ jD1jþjD2jþ

i

System modeling

The system under investigation consists of two area non-reheatthermal system with nonlinearity is given in Fig. 1 [21]. In Fig. 2, B$_1$and B$_2$ are the frequency bias parameters; ACE$_1$ and ACE$_2$ are areacontrol errors; u$_1$and u$_2$are the control outputs form the con-troller;R$_1$andR$_2$arethegovernorspeedregulation parameters

TLBOalgorithm

Teaching–Learning-BasedOptimization(TLBO)isanewlyintroduced metaheuristicalgorithmdevelopedbyRao[28].Itisanature-inspiredalgorithmwhichisbasedontheteacher-studentsinteractionprocessinaclassandproceeds toaglobalsolution.Asitisapopulationbasedalgorithm,soherethe

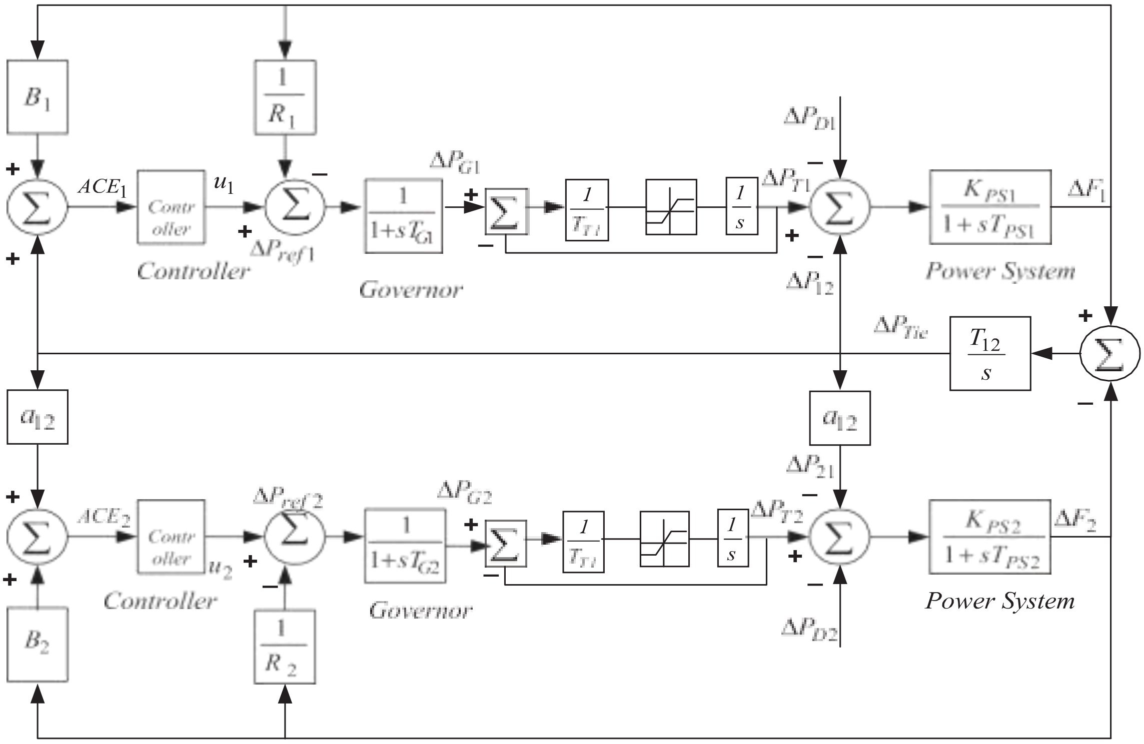

Fig.1.Twoareanon-linearthermalpowersystem.

population is taken as a group of learners or a class of learners andthe solution vector of the objective is analogous to the grade pointof different subjects offered to the learners in the class. The resultofastudentissimilartothatoffitnessfunction inotherpopulation-based techniques, to represent the quality of each solu-tion set. This algorithm is an efficient technique for solving nonlin-ear optimization problem. It is also a very fast algorithm as it takesa very few mathematical computations for updating the solutions.The whole process of TLBO algorithm is studied by dividing it into2phasesi.e.teacherphaseandlearnerphase.In teacherphase,stu-dents are motivated and enhanced their knowledge by the influ-enceofteacherconsideredas highly educated person. In thisway their academic results are improved by the teacher. In learnerphase, students not only learn from their teacher, but also learnfrom the mutual interaction among themselves which also helpsthem to improve their academic result. The knowledge of the stu-dentsisfinallyevaluatedonthebasisoftheiracademicresults.Theconceptandmathematicalformulationofteacherandlearnerphasesareasfollows.

Teacherphase

This phase of algorithm simulates the learning of the studentsthrough the teacher. During this phase the teacher conveys knowl-edge among the learners to improve the mean result of the class.Suppose there are ‘m’ no. of subjects (i.e. design problems) offeredto ‘n’ no. of learners (i.e. population size k = 1, 2, 3, … ,n) and insequential teaching–learning process i, M_{ji}be the mean results ofthe learners of a particular subject (j = 1, 2, … , m). Since the tea-cherisahighlyeducatedandmostexperiencedpersononthat subject,sointheentirepopulationtheteacheriscon sideredtobe the best learner in the class. Let $X_{total—kbest;i}$is the result of thebestlearnerconsideringallthesubjectsinthewholeclass,whois identified as the teacher of the class. Teacher will put maximumeffort to enhance the knowledge level of the entire class, but learn-erswillgaintheknowledgeaccordingtothequality ofteaching

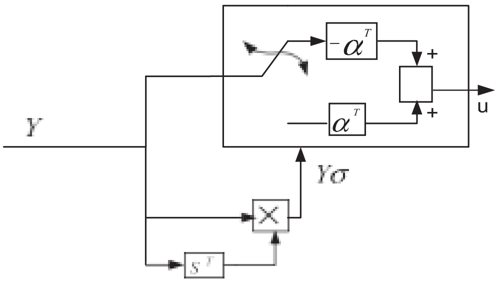

Fig.2.Blockdiagramofslidingmodecontroller.

deliveredbytheteacherandqualityoflearnerspresentintheclass.Consideringthisfactthedifference betweentheresultoftheteacherandmeanresultofthelearnersineachsubjectisexpressedas[29];

Differencemean$_{jki}$¼r$_i$ðX$_{jkbesti}$—T$_F$M$_{ji}$Þð7Þ

where X$_{jkbesti}$is the result of the best learner (i.e. the teacher) in thesubject j.T$_F$isthe teaching factor which decides the value of meanto be changed and r$_i$is the random number in the range [0, 1]. T$_F$isnotaparameterinthisTLBOalgorithmanditsvaluecanbeeither1or2.ThevalueofT$_F$israndomlydecidedas,

T$_F$¼roundð1þrandð0;1ÞÞ ð8Þ

Basedon,theexistingsolutionisupdatedisupdatedaccordingtothefollowingequation,

X$'_{jki}$¼X$_{jki}$þDifferencemean$_{jki}$ ð9þ

whereX$_{jki}$istheresultofthelearnersintheclassconsideringallthesubjects. X$_{jki}$is the updated value of. This is accepted if it gives thebettervalue.

All the accepted function values at the end of teacher phase aremaintainedandthesevaluesbecomeinputtothe learnerphase.

Learnerphase

This phase of the algorithm simulates the learning of the stu-dents through mutual interaction among themselves. The studentscan also enhance their knowledge by discussing or interacting withother students. Thislearning phenomenon canbe expressedasfollows.

Randomly two different learners i.e. P and Q are selected suchthatX$'_{total—Pj}$—X$'_{total—Qj}$.

WhereX$'_{total—Pj}$andX$'_{total—Qj}$areupdatedvaluesofX$_{total—Pj}$and X$_{total—Qj}$respectivelyattheendofteacherphase.

IfX$'_{total—Pj}$<X$'_{total—Qj}$

X$''_{jpi}$¼X$'_{jpi}$þriðX$_{jQi}$—X$'_{jPi}$þ ¼ ð10þ

IfX$'_{total—Qj}$<X$'_{total—Pj}$

X$''_{jpi}$¼X$'_{jpi}$þriðX$_{jpi}$—X$'_{jQi}$Þ ð11Þ

X$''_{jpi}$isacceptedifitgivesabetterfunctionvalue.Theflowchartfor theTLBOprocessisshownbelowinFig.3.

Resultandanalysis

ImplementationofTLBOalgorithm

The modelofthe systemunder studyshowninFig.1is devel-opedinMATLAB/SIMULINKenvironmentandTLBOprogramiswritten (in .m file). The relevantparameters are given inAppendix A. Thedevelopedmodel issimulated inaseparate pro-gram(by.m file) considering a 1% step load change in area-1.Theobjectivefunctioniscalculated inthe.mfileandusedintheoptimization algorithm. The process is repeated for each individualinthepopulation.Fortheimplementation ofTLBO,theparametersarerequiredtobespecified.Inthepresentstudy,apopulationsizeof N$_P$=100 and maximum number of iteration are also taken as 100. After several variations in N$_P$and maximum number of itera-tion, better results are obtained with N$_P$= 100 and maximum num-ber of iteration as 100. Note that increasing the population size N$_P$and maximum number of iterations beyond 100 will improve thesolution accuracy slightly at the expense of increasing the compu-tationtimesignificantly.Optimalvaluesoffeedbackgainsandswitching vector values are found considering the objective func-tionJ$_1$ are given in (12) and (13)with TLBO, (14) and (15)withPSOalgorithmand(16)and(17)withDE algorithmrespectively.

S 0:7244 0:4067 0:1864 0:0561 12
0:9440 0:4206 0:5961 0:5135

a 0:1858 0:0935 0:0566 0:0470 13
0:6827 0:4755 0:9270 0:4114

S 0:0218 0:8204 0:2875 0:8602 14

0:8602 0:5506 0:4572 0:850
Analysisofresults

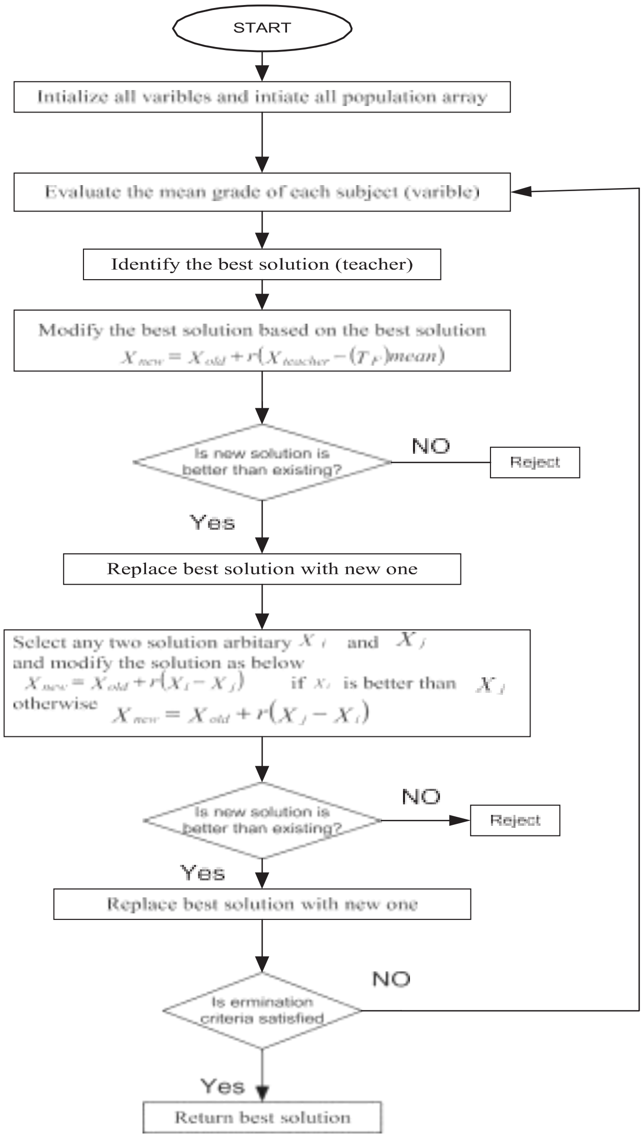

Fig.3.FlowchartofTLBOalgorithm.

a¼
S¼
0:2385 0:0509 0:135 0:5781
0:9044 0:7712 0:7041 0:4224
0:127 0:599 0:1312 0:1153
0:4411 0:2712 0:9441 0:5166
ð15Þ
ð16Þ ¼
Þb

Theperformanceofproposedoptimaloutputfeed backSMCtunedwithTLBOalgorithmiscompare dwith output feedbackSMCtunedwithPSOandstatefeedback SMCtunedwithGA[21]for the same objective function J_1 shown in Table 1. For propercomparison of control structure, same objective function and samepowersystemisconsidered.AsshowninTable1,thevalueof

a 0:4137 0:9148 0:4772 0:9162 17
0:4969 0:9276 0:7037 0:6946

objectivefunctionJ_1obtainedwith proposed controller withTLBO algorithm is 0.027 compared to 0.0272 with output feedbackSMCtunedDEalgorithm,0.0275withoutputfeedbackSMCtuned

Table1
SystemperformanceswithobjectivefunctionsJ_1.

Performance index	SMCwithoutputfeedbackcontrol withTLBO	SMCwithoutputfeedbackcontrol withDE	SMCwithoutputfeedback control withPSO	Statefeedbackcontrol [21]
J_1	0.0268	0.0273	0.0276	0.0375
Ts(inS) Df_1	1.3	1.4	1.52	1.9
Df_2	1.46	1.5	1.54	1.84
DPTie	1.05	1.1	1.24	1.15
OS Df_1	0.0011	0.0018	0.0016	0.0012
Df_2DPTie	2.422×10^{-4}	6.3897×10^{-4}	4.3015×10^{-4}	3.0562×10^{-4}
	2.8838×10^{-5}	7.6804×10^{-5}	8.0505×10^{-5}	3.9078×10^{-5}

with PSO algorithm and 0.0370 with state feedback control tunedwith GA [21]. Consequently, better system performance in termsminimum overshoot and settling times in frequencies and tie linepowerdeviationisachievedwithproposedTLBOoptimizedoutputfeedbackSMCcomparedto DEandPSOtunedoutputfeedbackSMCandstatefeedbackSMCtunedwithGA,whichemphasizesthe attribute of TLBO algorithm. Hence, it can be concluded thatproposed SMC controller tuned with TLBO algorithm outer permsthan the other techniques considered in this paper. So, for furtheranalysisoutputfeedbacktunedTLBOalgorithmisconsidered.

Dynamicresponseanalysis

To study the dynamic performance a step load change of 1% isappliedinarea-1att=0.Thesystemdynamicresponsesareshownin Figs. 4–6. It is seen from Figs. 4–6the better dynamic perfor-mances are obtained with proposed controller compared to outputfeedbackSMCtunedwithDEandPSOandstatefeedbackSMCtuned with GA [21]. Proposed TLBO optimized output feedbackSMC gives better dynamic performances in terms of relatively les-ser peak overshoot and lesser settling time compared to outputfeedback SMC tuned with PSO and DE techniques and state feed-backSMCtunedwithGA.

Sensitivity analysis

Sensitivity analysis is carried out to study the robustness of thesystem to wide changes in system parameters taking one at a time.Time constant of speed governor, turbine, tie-line power are chan-ged from their nominal values in range of20% to +20%. TheparametersofSMCobtainedwithnominalconditionarenotretuned,whenthesystemissubjected tovariationinsystemparameters. The performance of the system for a 1% step loadchange in area-1 is shown in Table 2under normal condition andvaried condition with proposed output feedback SMC tuned withTLBO algorithm. Critical examination of Table 2reveals that theperformance indexes are more or less same with nominal condi-tionandvariationinsystemparameters.Thedynamicresponses

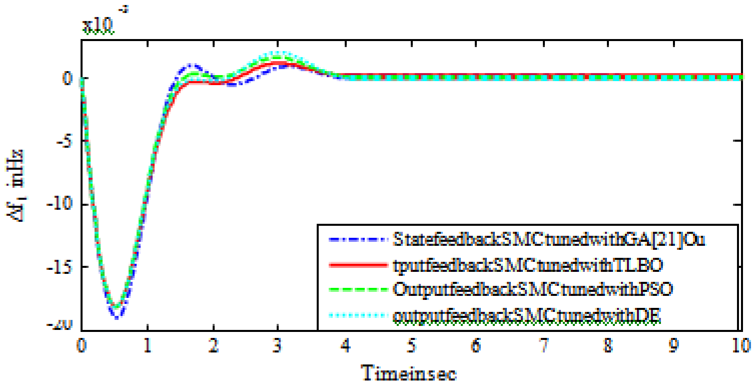

Fig.4.Frequencydeviationofarea-1for1%steploadchangeinarea-1.

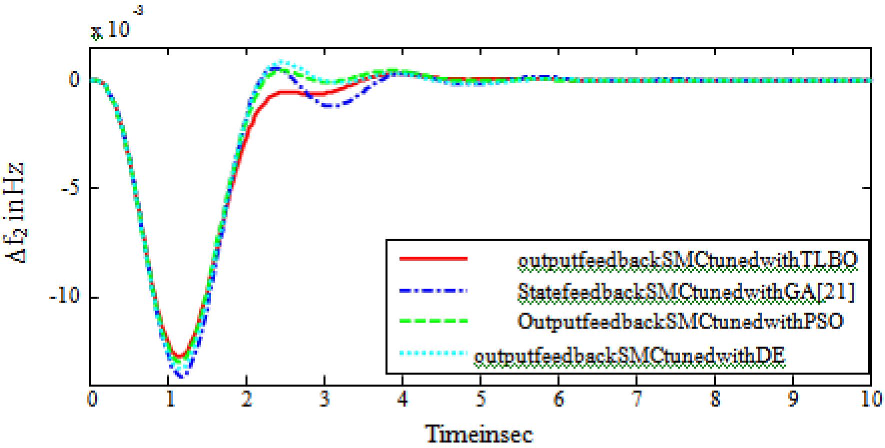

Fig.5.Frequencydeviationofarea-2for1%steploadchangeinarea-1.

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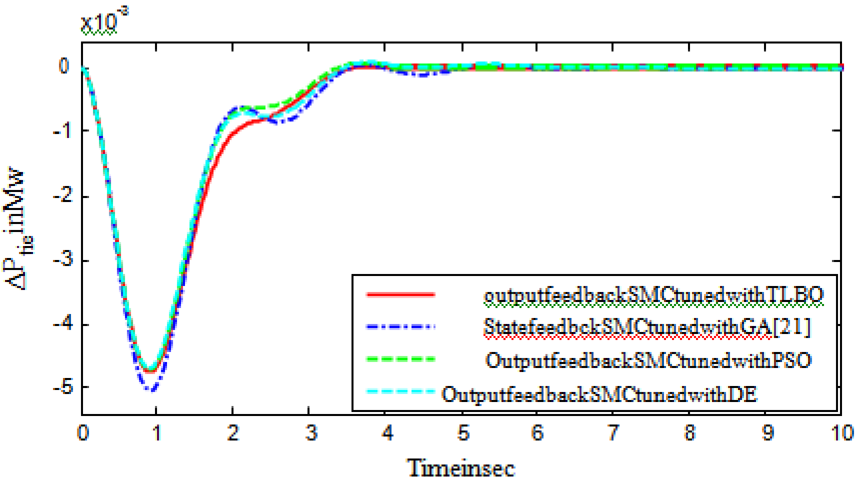

Fig.6.Changeintie-linepowerfor1%steploadchangeinarea-1.

ofthesystemwithvariationinsystemparametersfor1%steploadchange in area-1 are given in Figs. 7–9. It can be observed fromFigs. 7–9 that the effects of variation of parameters on the systemresponses are negligible. So, it can be concluded that the proposedcontrol provides robust and stable control satisfactorily. The opti-mum value of switching vector and feedback gains obtained withnominalparametersofthesystemneednotberesetforwidechangesinsystemparameters.

StatefeedbackSMCtunedwithGA[21]OutputfeedbackSMCtunedwithTLBO
OutputfeedbackSMCtunedwithPSO

outputfeedbackSMCtunedwithDE

Extensiontomulti-areamulti-sourcepowersystem

To explain the ability of proposed controller tuned with TLBOalgorithmcopeofwithmulti-sourcesmulti-area systems, thestudy is further extended to a multi-area multi-source intercon-nected realistic power systemwith/without HVDC link as shownin Figs. 10 and 11. A realistic power system proposed for the studyis consisting of reheat thermal, hydro, gas and nuclear as generat-ingunit.Thelinearizedmodelofgovernorreheatthermal,hydro turbine, gas turbine and nuclear turbine are shown in Fig. 10.

The transfer function model of thermal and hydro unit is consid-ered as given in [10]. The modeling of nuclear unit and its equiva-lenttransferfunctioninvestigatedisbasedon[26]. Eachunithas

Table2
Sensitivityanalysisoftwoareathermalsystem.

Parameter variation	%change	$ISE\times10^{-4}$	ITAE	$ITSE\times10^{-4}$	IAE	Settlingtime (inS) Df_1	Df_2	DP_{tie}
Nominal	0	7.0953	0.036	6.0187	0.0354	1.3	1.46	1.05
T_G	+20%	7.2989	0.0359	6.1551	0.0356	1.3	1.47	1.07
	—20%	6.8996	0.0361	5.8966	0.0352	1.33	1.44	1.04
T_T	+20%	7.7182	0.0383	6.6005	0.0369	1.3	1.51	1.08
	—20%	7.5883	0.0495	5.5927	0.0346	1.32	1.08	1.02
T12	+20%	7.1614	0.0366	6.0135	0.0358	1.51	1.37	0.97
	—20%	6.9868	0.0354	5.9949	0.0351	1.38	1.13	1.09

raising and 360% per minute for lowering generation in hydro areasare considered [18]. In Fig. 10, R_1, R_2, R_3 are the regulation param-eters of thermal, hydro and nuclear units respectively, U_T, U_H, $U_G$and$U_N$arethecontroloutputsforofthermal,hydro,gasandnuclear units respectively, K_T, K_H, $K_G$and $K_N$are the participationfactors of thermal, hydro, gas and nuclear generating units, respec-tively, $T_{SG}$is speed governor time constant of thermal unit in sec, $T_T$issteamturbinetimeconstantinsec,$K_r$isthesteamturbinereheatconstant, $T_r$is the steam turbine reheat time constant in sec, $T_W$isnominal starting time of water in penstock in sec, $T_{RS}$is the hydroturbinespeedgovernorresettimeinsec,T_{RH}ishydroturbinespeedgovernortransient droop timeconstant insec,T_{GH}ishydro turbine

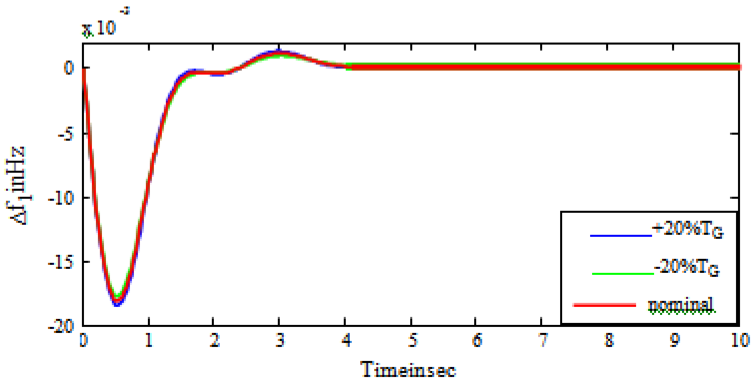

Fig.7.Frequencydeviationofarea-1for1%steploadchangeinarea-1withvariationin T_G.

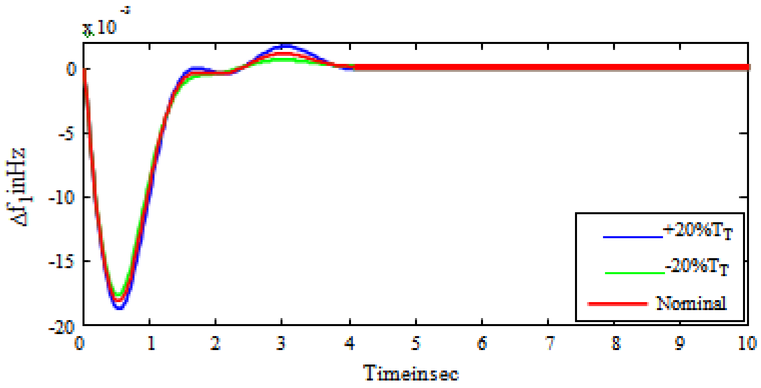

Fig.8.Frequencydeviationofarea-1for1%loadchangeinarea-1withvariationin T_T.

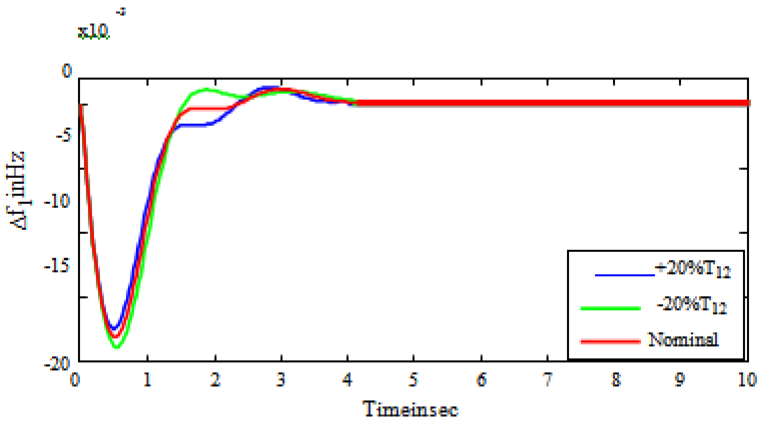

Fig.9.Frequencydeviationofarea-1for1%loadchangeinarea-1withvariationin T_{12}.

speed governor main servo time constant in sec, $X_C$is the lead timeconstant of gas turbine speed governor in sec, $Y_C$is the lag timeconstant of gas turbine speed governor in sec, $c_g$is the gas turbinevalve positioner, $b_g$is the gas turbine constant of valve positioner,$T_F$is the gas turbine fuel time constant in sec, $T_{CR}$is the gas turbinecombustion reaction time delay in sec, $T_{CD}$is the gas turbine com-pressor discharge volume-time constant in sec, $T_{GN}$is speed gover-nor time constant of nuclearunit insec,$K_{HI}$is gain of HP turbine,$K_{RI}$is gain of LP turbine of nuclear unit, T_{T1} is time constant of LPturbine, T_{RH1} is the time constant of first LP turbine in sec, T_{RH2} isthe time constant of second LP turbine in sec (detail of the nuclearpower plant is given in Appendix B

Fig. A1), K_{PS}power system gainin Hz/p.u. MW, $T_{PS}$is the power system time constant in sec,
DFistheincrementalchangeinfrequencyandDP_D incrementalloadchange.Theparametersofthepro posedsystemaregiveninAppendixB.Inthiscaseb othobjectivefunctionJ_1givenbyEq. (6)andobjectivefunctionISEgivenbyEq.(16)isc onsideredfor
comparison

J ISE
Ztsim f 2

The feedback gains and switching vectors of output feedbackSMC is optimized using TLBO algorithm. A 1% step load change isconsidered in area-1 and the optimization process is repeated for50 times. The best values of feedback gains and switching vectorobtainedcorrespondingtominimum objective function valuesaregiveninEqs.(19)and(20)forobjectivef unctionJ_1andEqs. (21)and(22)for objective function J_2 respectively for the systemhavingwithoutHVDC.

its regulation parameter and participation factor which decide thecontribution to nominal loading. In thermal power plants, powergenerationcanchangeonlyataspecifiedma ximum/minimumrateknownasGenerationRate Constraint(GRC).Inthepresentstudy,aGRCof3 %perminforthermalunitsand270%perminutefor

2 3
0:6988 0:6334 0:9646 9:2008
3:6906 0:8026 2:3631 9:9434
S¼6 7
¼4 5
9:093 7:9079 1:3515 5:5034
0:5384 6:7655 8:2228 9:114
2 3
9:4721 3:0486 7:7987 4:8723
5:4917 8:7822 9:8829 0:1915
a¼6 7
4 5
3:5132 5:3465 7:4782 9:7001
6:9514 9:7327 9:5114 9:0767

ð19Þ

ð20Þ

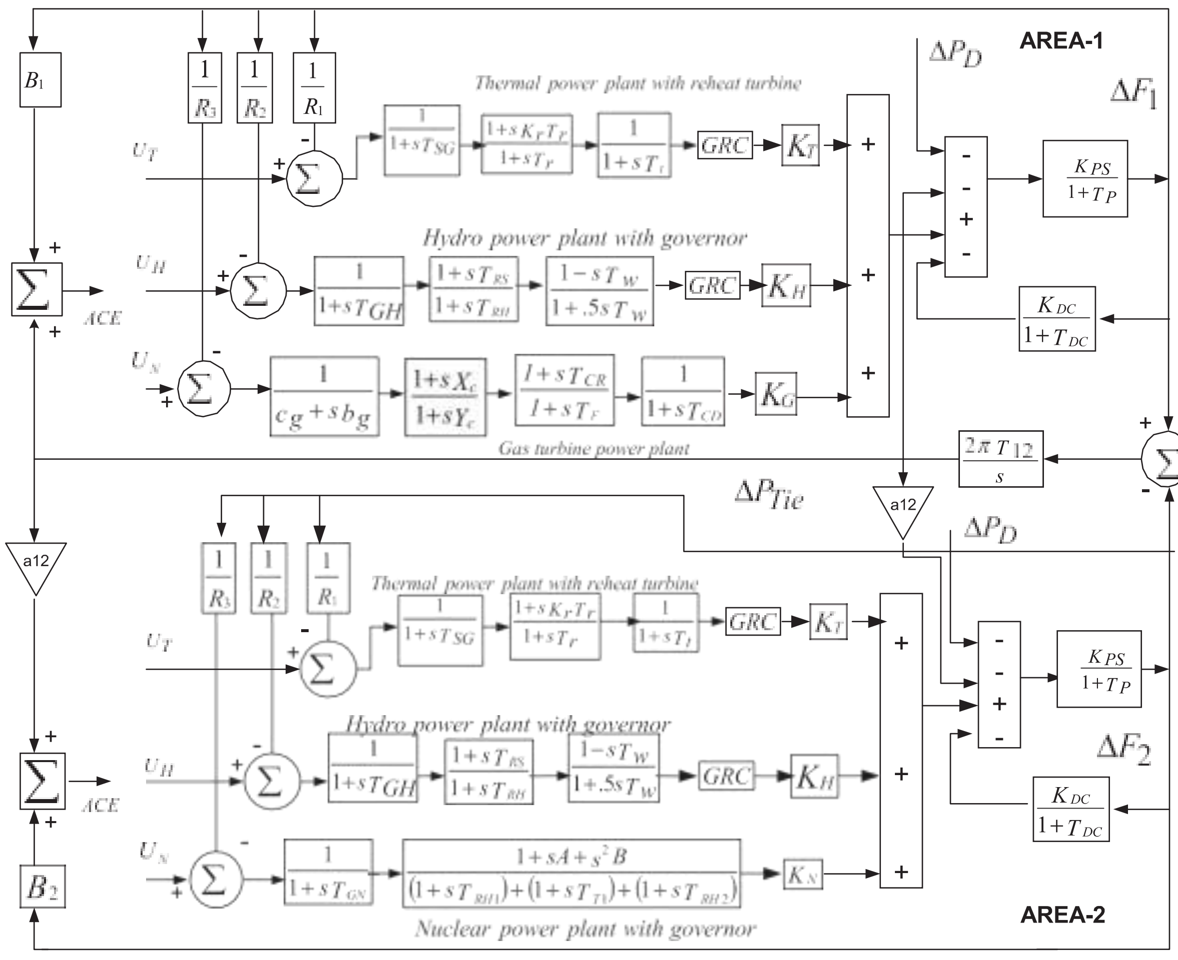

Fig.10.Blockdiagramofmulti-areamulti-sourceinterconnectedpowersystemwithHVDClink.

0:127 0:599 0:1321 0:1153 2 3
0:4411 0:2711 0:9441 0:5166
S ¼6 4 7 5
0:4453 0:3086 0:4696 0:7794
0:1688 0:0225 0:7087 0:6051

0:4137 0:9148 0:4772 0:9162 2 3
0:4969 0:9276 0:7037 0:6964
a ¼6 7
0:0046 0:5402 0:413 0:6281

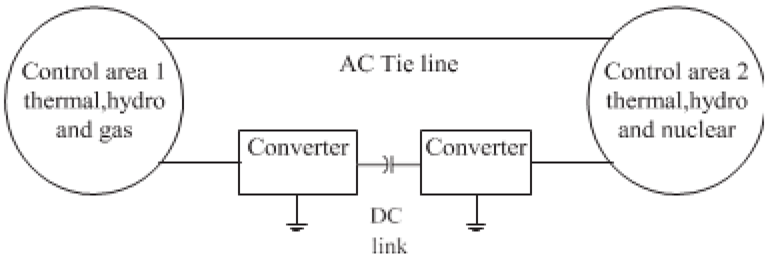

Fig.11.Systemunderstudy:TwoareapowersystemsinterconnectedthroughAC-DCparalleltielines.

2 7:8158 7:549 3:2622 5:2198 3
4 5
0:5435 0:216 0:5521 0:8627
0:9504 0:0164 0:1147 0:0124 2 3
0:2162 0:0111 0:6424 0:517
S ¼6 7
0:2455 0:1937 0:0909 0:3684
: : : :

ð25Þ
S¼6 6:4588 5:1124 6:621 2:3131 7
5
4
9:8257 0:8592 4:1268 9:8528
4:8526 6:1187 0:1122 7:6855
ð21Þ
4 5
00078 06027 04789 03081

1:014 2:1735 9:5269 2:6256
0:7864 2:2012 4:8499 5:153
a
8:3901 4:1315 4:0218 9:5269

ð22Þ
0:7444 0:8393 0:2624 0:5124
0:4468 0:3412 0:8391 0:9825
a
0:6265 0:1813 0:5800 0:3285
0:3285 0:2682 0:5502 0:1805

ð26Þ

4 5
3:351 1:3357 6:9544 9:2277

2 3

¼6 4 7 5

Similarly, with same procedure the feedback gain and switchingvectors are obtained for the given system with HVDC individuallyforobjectivefunctionJ_1isgiveninEqs .(23)and(24)andforobjec-tivefunctionJ_2isgivenbyEqs.(25)and(26)respectively.

Thevariousperformanceindices(settlingtime,overshoot,undershoot ITAE, ISE, ITSE, IAE and J_1) with/without HVDC aregiven in Table 3. With/Without HVDC the error values are reducedforobjectivefunctionJ_2comparedtoobjectivefunctionJ_1.Similarly,settlingtimeoffrequencyandtie-linepowerareimprovedforobjectivefunctionJ_2comparedtoobjectivefunction

Table3
Performanceindices,settlingtime,overshootandundershootwith/withoutHVDC.

Performanceindex		WithoutHVDCWithJ_2	WithoutHVDCWithJ_1	WithHVDCwithJ_1	WithHVDCwithJ_2
ITAE		1.187	1.5149	0.8672	0.3864
ITSE		0.0153	0.0182	0.0024	9.3287×10^{-4}
ISE		0.0075	0.0088	6.9392×10^{-4}	4.412×10^{-4}
IAE		0.2277	0.2355	0.0984	0.0611
J_1		1.2072	1.2504	0.6511	0.3996
Ts(inS)	Df_1	25.19	37.45	34.59	20
	Df_2	26.03	38.21	35.25	9.92
	DP_{Tie}	21.45	31.75	20.05	20.33
OS	Df_1	0.0051	0.0059	6.1294×10^{-4}	2.7741×10^{-4}
	Df_2	0.0037	0.0039	6.1563×10^{-4}	1.2757×10^{-4}
	DP_{Tie}	0.0011	0.0012	0.0013	8.4175×10^{-4}
US	Df_1	—0.0124	—0.0312	—0.0123	—0.0123
	Df_2	—0.0018	—0.0378	—0.0041	—0.0035
	DP_{Tie}	—0.0042	—0.0088	—0.0038	—0.0038

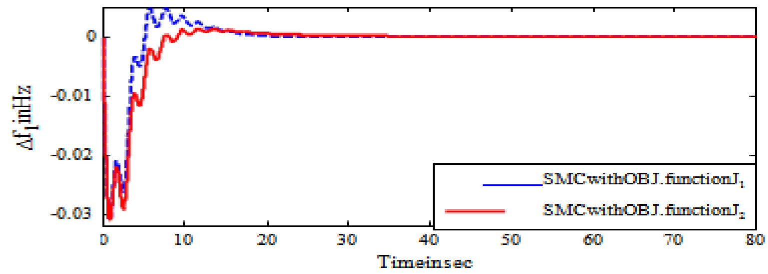

Fig.12.Frequencydeviationofarea-1with1%steploadchangeinarea-1withoutHVDC.

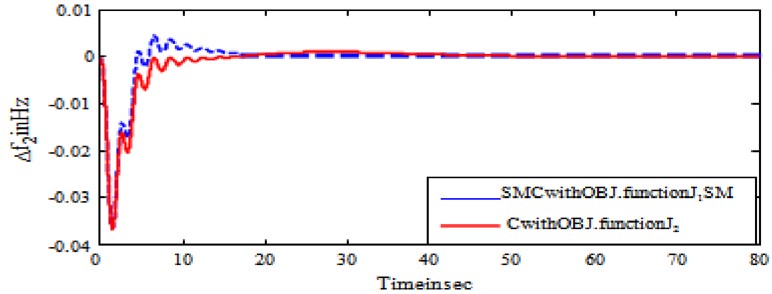

Fig.13.Frequencydeviationofarea-2with1%steploadchangeinarea-1withoutHVDC.

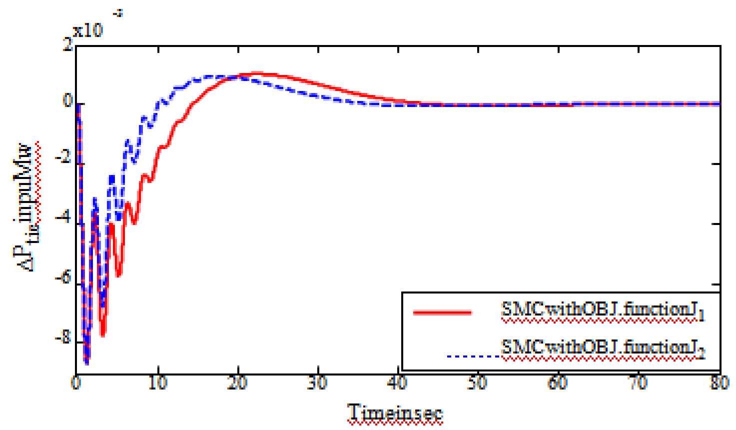

Fig.14.Changeintielinepowerwith1%steploadchangeinarea-1withoutHVDC.

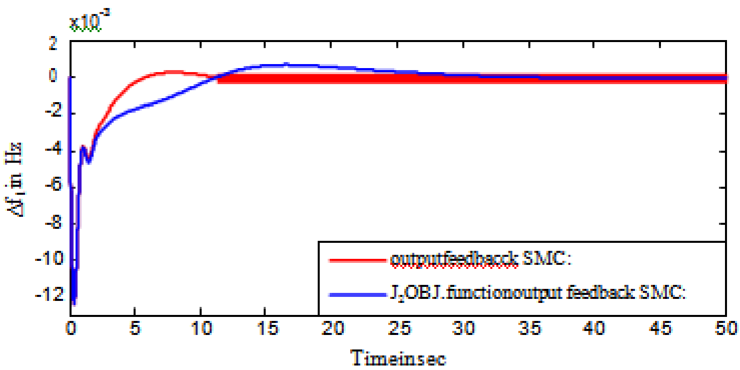

Fig.15.Frequencydeviationofarea-1with1%steploadchangein area-1 withHVDC.

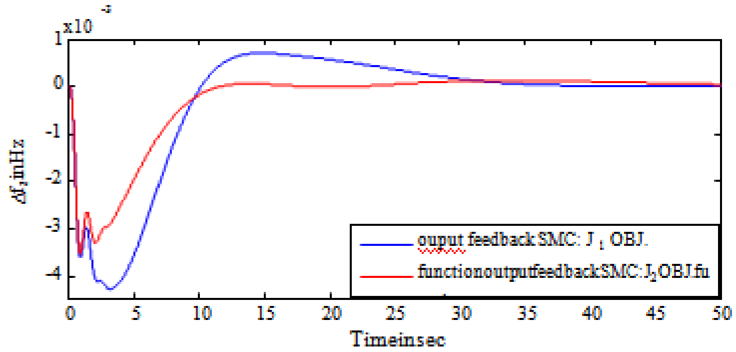

Fig.16.Frequencydeviationofarea-2 with 1% steploadchangein area-1 withHVDC.

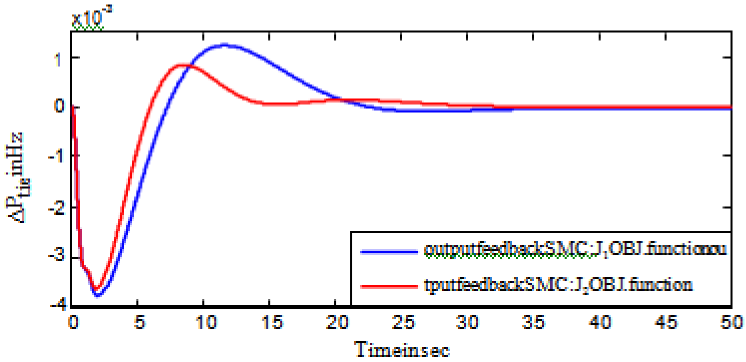

Fig.17.Changeintielinepowerwith1%steploadchangeinarea-1withHVDC.

Table4
SensitivityanalysisofmultisourcesystemwithHVDC.

Parameter variation	%change	ISE	ITAE	ITSE	IAE	Settlingtime(in S)		
						Df_1	Df_2	DPtie
Nominal	0	0.0004	0.3864	0.0009	0.0611	20	9.92	19.33
TSG1	+20%	0.0004	0.3869	0.0009	0.0611	19.98	9.92	20.27
	—20%	0.0004	0.3859	0.0009	0.061	20.04	10.2	20.39
TGH	+20%	0.0004	0.3874	0.0009	0.0612	20.03	9.95	20.33
	—20%	0.0004	0.3855	0.0009	0.061	19.94	9.93	20.29
T_R	+20%	0.0004	0.4242	0.0009	0.063	18.9	10.33	21.16
	—20%	0.0004	0.3772	0.0009	0.0604	20.8	9.57	19.38
TT1	+20%	0.0004	0.3879	0.0009	0.0612	20.09	9.88	20.31
	—20%	0.0004	0.3857	0.0009	0.0611	19.96	10.01	20.38
TRH	+20%	0.0004	0.4016	0.0009	0.0619	20.02	10.22	20.68
	—20%	0.0004	0.3637	0.0008	0.0599	20.08	9.6	19.85
T12	+20%	0.0004	0.3734	0.0009	0.0601	18.57	9.71	20.13
	—20%	0.0004	0.4094	0.0009	0.0626	21.5	10.3	20.63

-3
x 10

-3
x 10

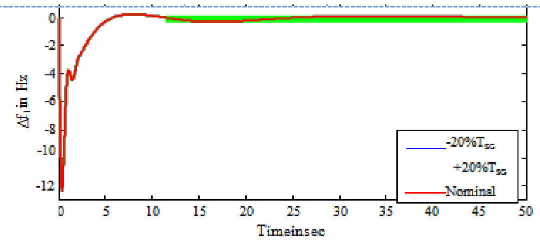

Fig.18.Frequencydeviationofarea-1for1%steploadchangeinarea-1withvariation T_{SG}

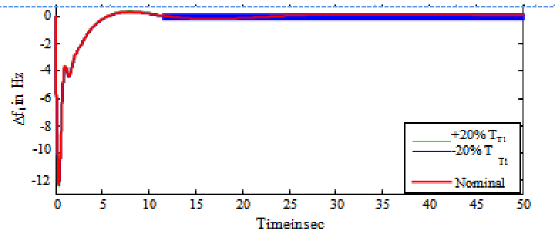

Fig.21.Frequencydeviationofarea-1forsteploadchangeinarea-1withvariationin T_T

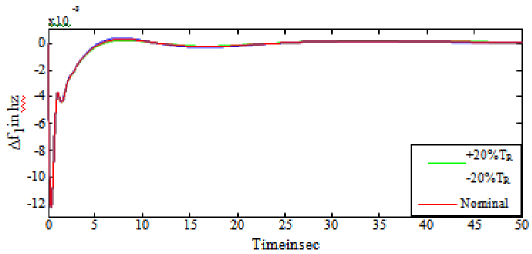

Fig.19.Frequencydeviationofarea-1for1%steploadchangeinarea-1withvariationin T_R

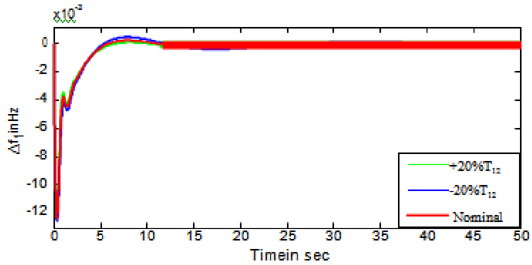

Fig.22.Frequencydeviationofarea-1for1%steploadchangeinarea-1withvariationin T_{12}

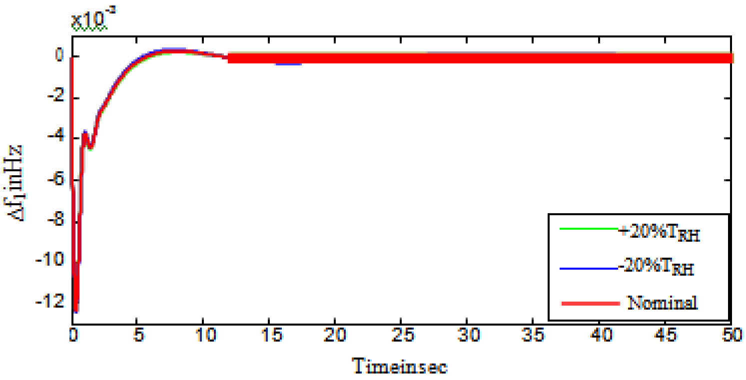

Fig.20.Frequencydeviationofarea-1for1%steploadchangeinarea-1withvariationin T_{RH}

J_1. It can be concluded that ISE is a better objective function than J_1considering system performance point of view. The performancesof the system are improved with HVDC link for both the objectivefunctions. Thedynamicperformancesofthesystemfor1%steploadapplied at area-1 without HVDC link is shown in Figs. 12–14. It isclear from Figs. 12–14; significant improvement is observed withobjectivefunctionISEcompared toobjective function J_1.Similarly,thedynamicperformancesofthesystemfor1%steploadchangewithHVDClinkareshowninFigs.15–17.

To study the robustness the system parameters changes in therange20% to +20% without changing the optimum parameter set-tingsofoutputfeedbackcontrolofSMC.Inall thecases,theparam-

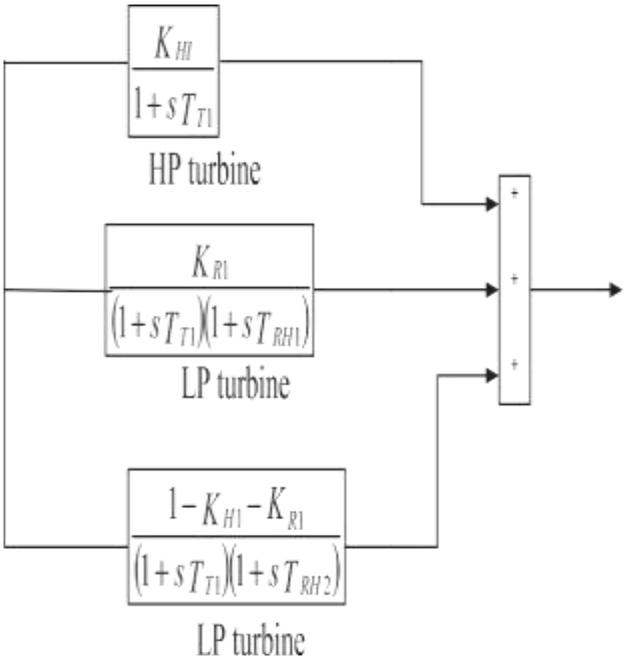

Fig.A1. IsolatedmodelofnuclearpowersystemofLFC.

ITSE, ISE, IAE, and settling time) under normal and parameter varia-tion cases for the system with HVDC is given in Table 4. It can beobserved that settling time, ITAE, ISE, ITSE and IAE values are variedwithin the acceptable range to their respective values for normalparametersetting.Hence,itcanbeconcludedthattheproposedcon-trollerarerobustandperformedsatisfactorilywith parametervari-ations.Thefrequencydeviationofarea-1for1%steploadchangeinarea-1 with variations in system parameter is shown in Figs. 18–22 Itcan be observed from Figs. 18–22 that there is negligible effect of thevariationofsystemtimeconstantsonthefrequencydeviationresponses with the controller parameters obtained at nominal val-ues. So it can be concluded that, the proposed control strategy pro-videsarobustandstable controlsatisfactorily.

CONCLUSION

In this paper, output feedback SMC tuned with TLBO has beenproposed for automatic generation control. Initially, two area ther-mal power system is considered and feedback gain and switchingvector of output feedback sliding mode controller are optimizedusingteachinglearningbasedoptimizationtechnique. To showthe superiority of proposed approach is compared to output feed-backSMCtunedwithPSOandstatefeedbackSMC tunedwithGA.It is observed that significant improvement is observed with theproposedcontrollercomparedtotherecentlypublishedresult.Alsorobustness analysisisperformed withvariationinsystemparameters in the range of20% to +20% from their nominal val-ues. The proposed approach is extended to two area non linearAGCsystemconsideringsixunitsofthermal,hydro,gasandnuclear power system with and without HVDC link. Results arecompared for with/without HVDC considering two objective func-tions. Also, sensitivity analysis is performed to show the robust-ness of the controller. It is observed that the parameters of theoutput feedback SMC controller obtained with nominal conditionneednottoberesetorretuned even if the system parametersarevariedinwiderange.

AppendixA

$B_1 = B_2 = 0.4312$ pu MW/Hz; P_{rt}= 2000 MW; P_L= 1840 MW;$R_1 = R_2 = R_3 = 2.4$ Hz/pu; T_{SG}= 0.08 s;T_T= 0.3 s; K_R= 0.3; T_R= 10 s;$K_{PS1} = K_{PS2} = 68.9566$ Hz/pu MW;$T_{PS1} = T_{PS2} = 11.49$ s;$T_{12} = 0.545$;a_{12} = —1; T_W= 1 s; T_{RS}= 5 s; T_{RH}= 28.75 s; T_{GH}= 0.2 s; K_{HI}= 2;K_{R1}=0.3;T_{T1}= 0.5s;T_{RH1}=7 s;T_{RH2} =9 s;K_T= 0.543478;
K_H=0.326084;K_N=0.130438.

AppendixB

$K_{HI}$is gain of HP turbine is 2, K_{R1} is gain of LP turbine of nuclearunitis0.3,T_{T1}istimeconstantofLPturbine is0.5 s,T_{RH1}isthetime constantoffirstHPturbineis7 s;T_{RH2}isthetimeconstantofsec-ondHPturbineis9 s.

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