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Optimal Power Flow Analysis of Interconnected Power System

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Abstract:
Electricutilitiesutilizevarioustechniquestoachieveoptimalpowerflow.InthispaperlinearprogrammingmethodandParticleswarmoptimizationmethodisusedforobtainingoptimalpowerflowusingequalityandinequalityconstrain.Toensuresecuredoperationofpowersystem,itisnecessarytokeepthelineflowwithintheprescribedMVAlimitsothatthesystem operates innormal state.Withtheinvolvement ofnonlinearfunctionand constrains,PSOmethod ismoresuitablethanlinearprogrammingmethod.
ThisapproachisexaminedandtestedonstandardIEEE6busand30bussystem.TestresultofPSOiscomparedwithlinearprogrammingmethodfordifferentcases.Theobtainedsolutionprovesthattheproposedtechniqueisefficientandaccurate.
Keywords:
Optimalpowerflow;LinearProgramming;Constrains;ParticalSwarmOptimization;SecurityConstrainedEconomic Dispatch

I. Introduction

Asthe powerindustrymoves into amore competitive environment,rigorousproceduresfor definingthelevelofinter-utilitypowerexchangesarerequired.OneoftheavailabletoolstoevaluatepowerexchangesamongutilitiesistheOptimalPowerFlow(OPF).TheuseofanOPFisbecomingincreasinglymoreimportantinsolvingtheproblem ofinter-utilitypowertransactionsinderegulatedelectricitymarkets.Throughouttheentireworld,theelectricpowerindustryhasundergoneaconsiderablechangein thepastdecade,andwillcontinuetodosoforthenextseveraldecades.Inthepast,theelectricpowerindustryhasbeeneitheragovernment-controlledoragovernment-regulatedIndustrywhichexistedasamonopolyinitsserviceregion.Allpeople,businesses,andindustrieswererequiredtopurchasetheirpowerfromthelocalmonopolisticpowercompany.Thiswasnotonlyalegalrequirement,butaphysicalengineeringrequirementaswell.Itjustdidnotappearfeasibletoduplicatetheresourcesrequiredtoconnecteveryonetothepowergrid[4].Overthepastdecade,however,countrieshavebeguntosplitupthesemonopoliesinfavourofthefree market.
Theoptimalpowerflowproblemhasbeendiscussedsinceitsintroduction.BecausetheOPFisaverylarge,non-linearmathematicalprogrammingproblem,ithastakendecadestodevelopefficientalgorithmsforitssolution.Manydifferentmathematicaltechniqueshavebeenemployedforitssolution.Themajorityofthetechniquesdiscussedintheliteratureuseoneofthefollowingfivemethods.

1. Lambdaiterationmethod
2. Gradientmethod.
3. Newton’smethod
4. Linearprogrammingmethod.
5. Interiorpointmethod.

TheLinearProgramming(LP)approachtransformsthenonlinearoptimizationproblem intoaniterativealgorithm thatin eachiterationsolvealinear optimizationproblemresultingfromlinearizing boththe objectivefunctionandconstrains. Thelarge-scaleapplicationofLP-basedmethodshastraditionallybeenlimitedtonetworkconstrainedrealandreactivedispatchcalculationswhoseobjectivesareseparable,comprisingthesumofconvexcostcurves.Theaccuracy ofcalculationmaybelostiftheoversimplifiedapproximationisadoptedinLP-basedOPF.Thepiecewiselinearsegmentationofthegeneratorfuelcostcurveshouldbegoodforavoidingthisproblem.Thepiecewiseapproachcanfitanarbitrarycurveconvexlytoanydesiredaccuracywithasufficientnumberof segments.Originally, aseparableLP variablehad to beusedfor eachsegment,withthe resultinglarge problemswithmultisegmentscostcurvemodelingwereprohibitivelytimeandstorageconsuming[3].
NowdaysadvancementincomputingandparallelprocessingenablesthepopulationbasedsearchprocedurelikeGenetic Algorithm,EvolutionaryProgrammingandParticleSwarmOptimizationtoapplyintherealtimeapplicationslikeOPF[2].InthispaperTheParticleSwarmOptimizationmethodisappliedtosolveOptimalPowerFlow.Theeffectivenessoftheproposedmethodisprovedbyapplyingitfora6busand30bussystem.

II. Overview

- **Linearprogrammingmethod**:

Linearprogrammingmethodisveryadaptathandlingconstrains,aslongasproblemtobesolvedislinearizedwithoutlossof accuracy.Inthistechniquenonlinearcostfunctionofgeneratorarelinearizedfirst.Thosefunctionaredividedintosmallpar tsasshowninfigure.

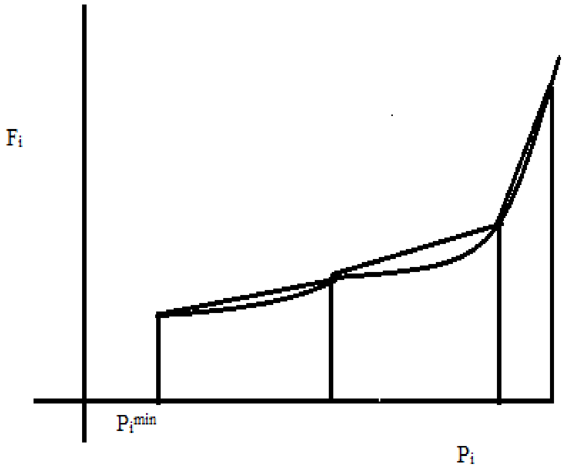


Fig.1: Linearizationofcostcurve

AsshowninfigureF$_i$iscostofthatgeneratorandP$_i$isthepowerproducedbythegenerator.Withthehelpofthislinearization thismethodisusedwithease[1].

- **ParticleSwarmOptimization**:

ThePSOisbasedontheresearchesonsocialbehaviorooforganismssuchasfishschoolingandbird-flockingprovidesapopulation-basedsearchprocedureinwhichindividualscalledparticleschangetheirpositions(states)withtime.Whileflyinginamultidimensionalsearchspace,eachparticleadjustsitspositionwiththenewvelocitywhichdependsonitsownexperience(pbest)andtheexperienceofneighboringparticles(gbest),
i.e makinguseofthebestpositionencounteredbyitselfanditsneighbors.
Letxandvdenoteaparticlecoordinates(position)anditscorrespondingflightspeed(velocity)inasearchspace,respectively.Theithparticleisrepresentedby,
$x_i=(x_{i1},x_{i2},.....x_{id})$inthed-dimensionalspace.
Thebestpreviouspositionofthe i^{th}particleis
$pbest_i=(pbest_{i1},pbest_{i2},.....,pbest_{id})$.
Theindexofthebestparticleamongallparticlesinthegroupisrepresentedbythe*gbest*.Therateofthe velocityforparticle'i'isrepresentedas:
$v_i=(v_{i1},v_{i2},.......,v_{id})$.
The modifiedvelocityandpositionofeachparticlecanbe calculatedusingthecurrentvelocityandthe distancefrom$pbest_{ij}$and$gbest_i$asshowninthefollowingformulae:

$v_{ij}(t+1)=w(t)*v_{ij}(t)+c_1*rand()*(pbest_{ij}-x_{ij}(t))+c_2*Rand()*(gbest_j-x_{ij}(t))$ (1)
$x_{ij}(t+1)=x_{ij}(t)+v_{ij}(t+1)$ (2)
$i=1,2,.........,n;j=1,2,.......,d$ (3)
where,
n–Numberofparticlesinapopulation(Populationsize)
d-Numberofvariablesinaparticlet-Iterationcount
w-Inertiaweightfactor
c_1,c_2-Accelerationconstants
rand(),Rand()-Uniformrandomvalueintherange[0,1];v(t)-Currentvelocityofiparticleattiteration,vjminvij (t)vj,x(t)-Currentpositionofiparticleattiteration.

Intheaboveprocedure,iftheparameterv$_{max}$istoohigh,particlesmightflypastgoodsolution.Ifv$_{max}$istoo$_{small}$, particlesmay not exploresufficientlybeyondlocalsolution. Theconstantsc andc representtheweightingofthestochasticaccelerationtermsthatpulleachparticletowardthepbestandgbestpositions.Suitableselectionofinertiaweightwin(4)providesabalancebetweenglobalandlocalexplorations,thusrequiring less iterationonaveragetofindasufficientlyoptimalsolution,inertiaweightwis setaccordingtothefollowingequation.

$w(t)= w_{max}-\{(w_{max}-w_{min})/t_{max}\}*t$ (4)

wheret$_{max}$isthemaximumnumberofiterations(generations)and‘t’isthecurrentnumberofiterations[5][6].

III. Problem formulation

- **Linearprogrammingmethod**

The OPF problemis to optimizethesteadystateperformanceof powersysteminterms ofanobjectivefunctionwhilesatisfyingseveralequalityandinequalityconstrains.Mathematically,theproblemcanbeformulatedasfollows[5].

MinJ(x) (5)
Subjecttog(x)=0 (6)
Andh(x)≤0 (7)
NowJisourobjectivefunctionwhichisgeneratorcost.Jisminimizedwithrespecttog.Objectivefunctionconsistofx.Here xisactivepowerofeachgenerator.

EqualityConstrains: Mostlygeneratorpowerisoptimizedwiththisconstrain.Hereinthispaperequalityconstrainisgive bygeneratedpowershouldbeequaltoloadandlosses[4][1].

$P_{gen}=P_{load}+P_{loss}$ (8)

Inequalityconstrains:Generatorpower,linepower,generatorvoltagecanbeoptimized withinequality constrains.Hereinthispaperinequalityconstrainisimplementedbyforanyithlinelineflowf$_i$shouldnotviolateitsmaximumf$_i^{max}$andminimumf$_i^{min}$limits.

$f_i^{min} \le f_i \le f_i^{max}$ (9)

Hencewiththehelpofinequalityconstrainlinepowerlimitismaintained.

Objectivefunction:Objectivefunctioninlinearprogrammingishavingcontrolvariables.Thuswiththehelpofcontrolvariablesobjectivefunctionisoptimized.Objectivefunctioninthispaperisconsideredasthegenerator`soperatingcostandgeneratorpoweriscontrolvariable.Hencegeneratorsoperatingcostistobereduced. Thiscost functioncanbeoptimizedwiththehelp ofeconomicalloaddispatch.Objective functionwillbedifferentforeachperticulargenerator.Heregeneralizefunctionisshown

$F_i (P_i)=a_i+b_iP_i+c_iP_i^2$ (10)

Herea$_i$,b$_i$,c$_i$aregeneratorscostcoefficients.Thisparametersaredifferentforeachgenerators.

- **ParticleSwarmOptimization**

IntheOptimalPowerFlowwithLineFlowConstraints,minimizationofeitherthecostofgenerationorrealpower lossmaybe consideredasobjective function'f'. Thecontrolvariable 'u'maybetakenaseither a vectorofrealpowergeneratedorthegenerationvoltageorbothdependsontherequirement.Mathematically,itcanbeformulatedas,

Minf(x,u) (11)
subjectto (12)
g(x)=0 (13)
$P_{gmin}(i)P_g(i)P_{gmax}(i)$ (14)
$U_{min}(i)U(i)U_{max}(i)$ (15)
$S(i,j)S_{max}(i,j)$ (16)

Theequations(13)to(16)representstheconstraintsonthepowerbalance,maximumgenerationlimit,systemvoltagelimitsandlineflowlimitsrespectively.

IV. Implementation

- **Linearprogrammingmethod:**

Theabovementionedmethodforsolvingoptimalpowerusesaniterativetechniquetoobtaintheoptimalsolution,soitisalso calledaSuccessiveLinearProgramming(SLP)method.ThesolutionproceduresofSLPforoptimalpowerflowaresummarizedbelow:

1. Selectthesetofinitialcontrolvariables.
2. Solvethepowerflowproblemtoobtainbasepowerforproposedsystem.
3. Preparelinearobjectivecostfunctionandrunlinearprogrammingtofindpowervalues.
4. Enterthispowervaluesinpowerflowandgetnewvaluesofpower(Powerflow1).
5. Checkallgeneratorvalueswithitsmaximumandminimumvaluesandifit`sviolatedthansettheirlimits.
6. ThenselectthenewlossvaluesofpowerflowandrunLP.
7. GetLP-1resultandfromthatgetnewvaluesofgeneratorpowers.
8. Putthosevaluesinobjectivecostfunctionandcheckwhethercostisoptimizedornot.
9. Thencheckallthe minand maxlimitsofgeneratorandlinepowerand withthehelpofconstraints.
10. Minimizetheparametersoneswho`soutofmaxlimits.

Thesestepsareappliedonourproposed systemwiththe helpofMATLAB programming.Forcalculatinglinearprogrammingweneedgeneratorcostfunctioninsegmentslopes.Itsequationis

$$S_{ij}= F_i(P_i)^+ - F_i(P_i)^- \div (P^+_{ij} - P^-_{ij}) \quad (7)$$

- **ParticleSwarmOptimizationAlgorithm**

Step1:InOPFproblem,eachithparticleisrepresentedby$x_i=(x_{i1},x_{i2},…..x_{id})$,where'x'consistsofsetofcontrol variables‘u’,Realpowergenerationorvoltageorbothofall theunits.Initializerandomly theindividuals(particles)ofinitialpopulation(thesizeofpopulationmatrixisnXd)andvelocitiesaccordingtolimitsofeachvariable.
Step2:Toeachindividualxofthepopulation,runtheloadflowprogramtofindthesystemvoltagesofdependentandcontrolledbuses,realandreactivepowergenerationofslackbusandcontrolledbuses,MVAflowsoftransmissionlinesandtotalrealpowerloss.Theexecutionofloadflowensurestosatisfytheconstraint.Here,inthispaper,fullNewtonmethodisused foritsaccuracy[7].
Step3:Forallthe individuals,calculate theobjectivefunctionvalue'f'that maybe the totalcostofgenerationorthetotalrealpowerloss.Foranyindividual,ifanyoftheconstraintsspecifiedby(6)to(8)isviolated ,addpenaltytoitsobjectivefunction
Step4:Eachinitialsearchingpointisassignedaspbestoftheindividualandthebestevaluatedvalueamong pbest’sissetasgbest.
Step5:Modifythevelocityofeachindividual$x_i$accordingto(1).Ifanynewvelocityexceedsitslimitsetitatthelimit.
Step6:Modifythe positionofeachindividualaccordingto(2).The modifiedvaluesmust satisfythe constraintsontheirlimits.
Step7:Findtheobjectivefunctionforthe newpositioninthesame wayasinitialpositions(Steps2&3).
Step8:Compareeachindividual’sobjectivefunctionvaluewithitspbestandiftheobjectivefunctionofthenewpositionislessthanpreviouspbest,assignthepresentpositionaspbest.Thebestevaluatedvalueamongpbest’sisdenotedasgbest.
Step9:Repeatthestepnumbers5to8untilthe numberofiterationsreachesthemaximum.
Step10:Thelatestvalueofgbestistheoptimumsolutionthatminimizestheobjectivefunction.[9]

V. Proposed system

StandardIEEE6busand30bussystemareusedforapproachingtheproposedmethods.

- IEEE6bussystem:

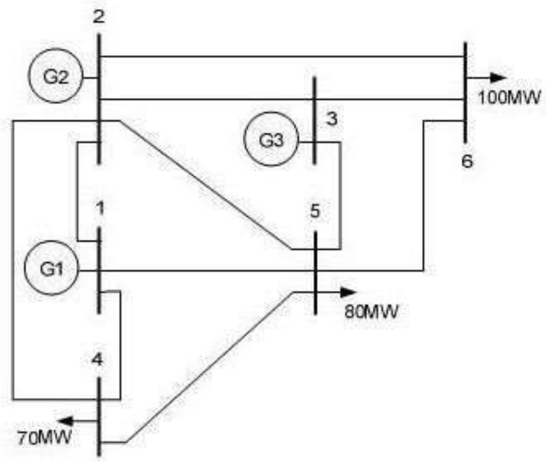
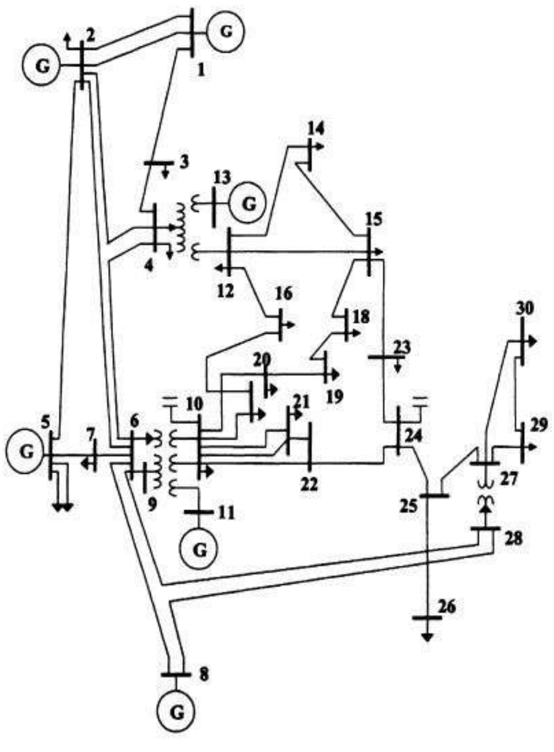


Fig.2:6Bussystem

In6bussystem 3generatorsareusedtomeetupdemand.Inthatbus1istakenasslackbus.Totalloadforthissystemis210MWandlossesare8.57MW.

- IEEE30bussystem:Fig3shows30bussystem[8]



Asshowninfig30bussystemconsistof6generators.Totalloadforthissystemis259.30MWandlossesare 17.59 MW.Bus1istakenasslackbus.

VI. Results And Discussion

TheproposedalgorithmofParticleswarmoptimizationisimplementedona6busand30bussystemandtheresultsarecomparedLinearProgrammingmethod.

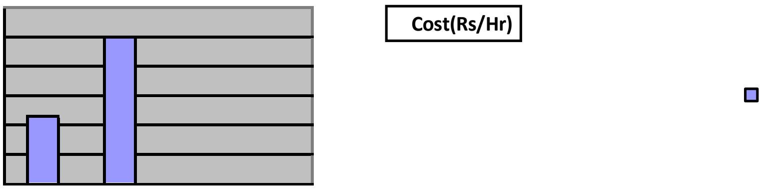
PoweroutputsofthreegeneratorsareconsideredasthecontrolvariableandOPFisexecutedtominimizetheoperatingcost givenby

n

$f(u)=a_iP_{gi}^2+b_iP_{gi}+c_i$(9),i=1andu=[Pg1Pg3...Pgn]

- Resultsof6bussystem:

3132
3130
3128
3126
3124
3122
3120



PSO **LP**

Fig4: Generatoroperatingcost

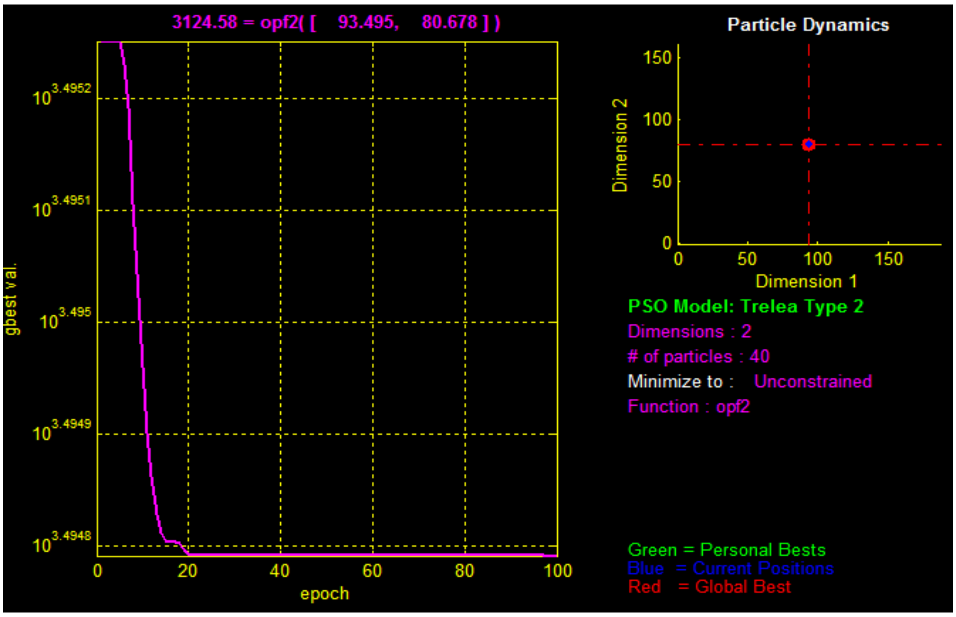
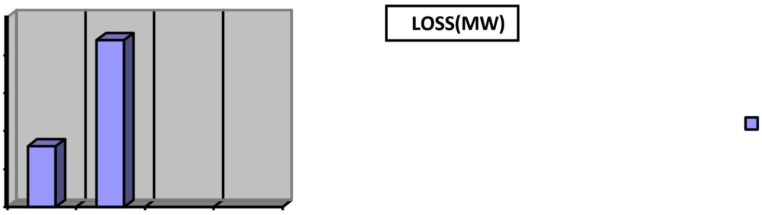


Fig5: ConvergencecharacteristicofPSOfor6bussystem

6.9
6.85
6.8
6.75
6.7
6.65

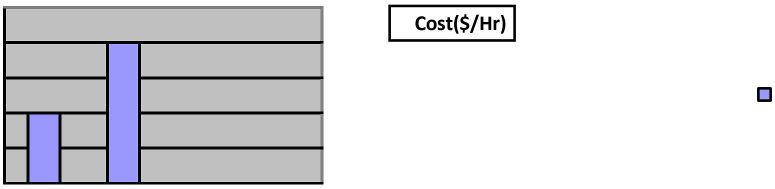


PSO **LP**

Fig6: Lossesin6busSystem

- Resultsof30bussystem

3200
3000
2800
2600
2400
2200



PSO **LP**

Fig.7Generatoroperatingcostfor30bus

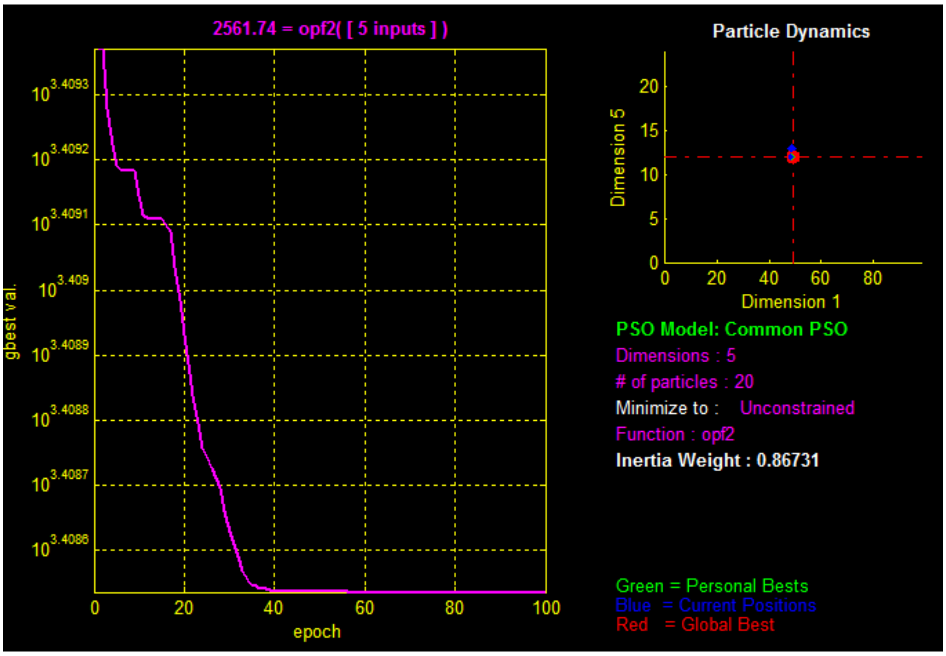


Fig.8: ConvergencecharacteristicofPSOfor30bussystem

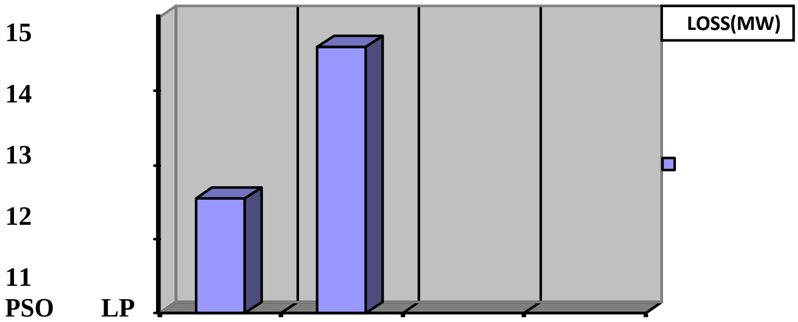


Fig9: Lossesin30bussystem

Abovefigures showsthat effectivenessofthe proposedPSOapproachcompared to linear programmingmethodasgeneratingcostofgeneratorsaredecreasingcomparedtolinearprogrammingmethod. AsproposedapproachPSOisimplementedonbothsystemtotallossesarealsodecreasing.Thusitisalsoseenthatalltheline sare withintheirMVAlimits.

- **ParameterSelection:**

Forthetestsystemconsidered,thefollowingPSOparametersarechosenafteratrialanderrorprocess.v_{max}=10%of'x';v_{min}=0;w_{max}=0.9;w_{min}=0.4;c_1=2;c_2=2;Populationsize=24;Maximumnumberofiterationis foundtobe100.

VII. Conclusion

Nowdays,asrestructuringofpowersystemincreasesthecongestionof powerflowinthetransmissionsystem,theOptimalPowerFlowplaysanimportantroleindaytodaypowersystemoperationandcontroltomaintainsystemsecurity.ParticleSwarmOptimizationtechniqueisfoundtobehighlysuitableforOptimal PowerFlowproblemwithlineflowconstraints.Withthehelpofequalityconstrainsandinequalityconstrainsvariousparameterslikegeneratorpower,linepower,generatoroperatingcost,reactivepowercanbeoptimized.Itisalsoassuredthatthe algorithmwouldfunctioninthesamewayforlargepowersystemswithmorenumberoflinesandgeneratingunits.Thecomputationalresultsofthesamplesystemrevealthattheproposedmethodismuchmoreefficientandversatilethanotherlinear programmingmethod.

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Appendix

- **6busdata:**

Busdata

Busnumber	BusType	Voltage(pu)	Pgen. (pu)	Pload(pu)	Qload(pu)
1	1	1.05	-	-	-
2	2	1.05	0.50	0	0
3	2	1.07	0.60	0	0
4	0	0	0	0.7	0.7
5	0	0	0	0.7	0.7
6	0	0	0	0.7	0.7

Linedata

FromBus	To Bus	R(pu)	X(pu)	Shunt(pu)	Linelimit(MWA)
1	2	0.10	0.20	0.02	40
1	4	0.05	0.20	0.02	60
1	5	0.08	0.30	0.03	40
2	3	0.05	0.25	0.03	40
2	4	0.05	0.10	0.01	60
2	5	0.1	0.30	0.02	30
2	6	0.07	0.20	0.025	90
3	5	0.12	0.26	0.025	70
3	6	0.02	0.10	0.01	80
4	5	0.20	0.40	0.04	20
5	6	0.10	0.30	0.03	40

Generatorcostcoefficient

Generator	a_i	b_i	c_i	PGmin(pu)	PGmax(pu)	Qmax (pu)
1	0.00533	11.669	213.1	50	200	-
2	0.00899	10.333	200	37.5	150	70
3	0.00741	10.833	240	45	180	70

- **30busdata**

Busdata

Bus no	Bustype	Voltage(pu)	Pgen(MW)	Pload(MW)	Qload(MW)
1	1	1.06	0	0	0
2	2	1.043	40	21.70	12.7
3	0	1	0	2.4	1.2
4	0	1.06	0	7.6	1.6
5	2	1.01	0	94.2	19
6	0	1	0	0	0
7	0	1	0	22.8	10.9
8	2	1.01	0	30	30
9	0	1	0	5.8	0
10	0	1	0	0	2
11	2	1.082	0	11.2	0
12	0	1	0	0	7.5
13	2	1.071	0	6.2	0

14	0	1	0	8.2	1.6
15	0	1	0	3.5	2.5
16	0	1	0	9	1.8
17	0	1	0	3.2	5.8
18	0	1	0	9.5	0.9
19	0	1	0	2.2	3.4
20	0	1	0	17.5	0.7
21	0	1	0	0	11.2
22	0	1	0	3.2	0
23	0	1	0	8.7	1.6
24	0	1	0	0	6.7
25	0	1	0	3.5	0
26	0	1	0	0	2.3
27	0	1	0	0	0
28	0	1	0	2.4	0
29	0	1	0	0	0.9
30	0	1	0	10.6	1.9

Linedata

FromBus	ToBus	R(pu)	X(pu)	Shunt(pu)	Linelimit(MWA)
1	2	0.0192	0.0575	0.02640	130
1	3	0.0452	0.1852	0.02040	130
2	4	0.0570	0.1737	0.01840	65
3	4	0.0132	0.0379	0.00420	130
2	5	0.0472	0.1983	0.02090	130
2	6	0.0581	0.1763	0.01870	65
4	6	0.0119	0.0414	0.00450	90
5	7	0.0460	0.1160	0.01020	70
6	7	0.0267	0.0820	0.00850	132
6	8	0.0120	0.0420	0.00450	20
6	9	0.0	0.2080	0.0	65
6	10	0	.5560	0	32
9	11	0	.2080	0	65
9	10	0	.1100	0	65
4	12	0	.2560	0	65
12	13	0	.1400	0	65
12	14	.1231	.2559	0	32
12	15	.0662	.1304	0	32
12	16	.0945	.1987	0	32
14	15	.2210	.1997	0	16
16	17	.0824	.1923	0	16
15	18	.1073	.2185	0	16
18	19	.0639	.1292	0	16
19	20	.0340	.0680	0	32
10	20	.0936	.2090	0	32
10	17	.0324	.0845	0	32
10	21	.0348	.0749	0	32
10	22	.0727	.1499	0	32
21	22	.0116	.0236	0	32

15	23	.1000	.2020	0	16
22	24	.1150	.1790	0	16
23	24	.1320	.2700	0	16
24	25	.1885	.3292	0	16
25	26	.2544	.3800	0	16
25	27	.1093	.2087	0	16
28	27	0	.3960	0	65
27	29	.2198	.4153	0	16
27	30	.3202	.6027	0	16
29	30	.2399	.4533	0	16
8	28	.0636	.2000	0.0214	32
6	28	.0169	.0599	0.065	32

Generatorcostcoefficient

Generator	a_i	b_i	c_i	PGmin(pu)	PGmax(pu)	Qmax(pu)
1	0.00375	2	0	50	200	-
2	0.0175	1.75	0	20	80	-
3	0.0625	1	0	15	50	-
4	0.0083	3.25	0	10	35	-
5	0.025	3	0	10	30	-
6	0.025	3	0	12	40	-