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ANon-linearPower Electronic Converter withUniversalFuzzyController

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Abstract---**This paper presents the development of a universalfuzzy controller for a non-linear power electronic converter.Theclassicalboostconverterusedinpowersupplies is aminimalphase system with a right-half-plane zero. This right-half-planezeroforcesthedesignertogoforcontrollersthatgiveslowdynamics.TheconventionallinearPIcontrollersforsuchconverters,designedundertheworstcaseconditionsofmaximum load and minimum line conditions, present a lowerloopbandwidthevenifttheoperatingconditionsarebetter.Moreover,thesystemresponseissluggish.Modernfuzzycontrollers,ontheotherhand,canbedesignedtoadapttovarying operating conditions for application in such nonlinearsystems.Thispaperdesignsauniversalfuzzycontrollerand compares its performance at various operating points with localPI controllers designed for the particular operating points. Thesettlingtimeandovershootforstartupandstepresponseobtained bycomputersimulationshavebeencompared.Thesuperior performance of the fuzzy controller, in particular, itsabilitytoachievegoodtransientresponseunderdifferentoperating conditions is clearlyestablished.**

Keywords:BoostConverter,Right-Half-PlaneZero,DC-DCConverter; Small signal analysis, fuzzylogic.

I. INTRODUCTION

Traditionalfrequencydomainmethodsfordesignofcontrollersforpowerconvertersarebasedonsmallsignalmodeloftheconverter. Thesmallsignalmodeloftheconverter has restricted validity and changes due to changes inoperating point. Also the models are not sufficient to representsystems with strong non-linearity. Moreover, the performanceof the controllers designed by frequency domain methods isdependent on the operating point, the parasitic elements of thesystem, and the load and line conditions. Good large signalstability can be achieved only by decreasing the bandwidth,resultingin slow dynamics.

A state-space averaged model of the classical boost DC-DCconverter suffers from the well-known problem of Right-Half-Plane(RHP)zero[1-3]initscontrol-to-outputtransferfunctionundercontinuousconductionmode(CCM).Themovement of the zero on the complex S-plane as the operatingpoint changes further compounds the problem. Designers aregenerally forced to limit the overall closed loop bandwidth tobe much less than the corner frequency due to the worst caseRHP zero location, which typically restricts the bandwidth to1/30th of the switching frequency [1]. As a result of this, thesystemhasasluggishsmallsignalresponseandapoorlargesignal response.

To achieve fast dynamic response, there are two possibleroutes as suggested by Tse et al. [4]. One way is to develop amoreaccuratenon-linearmodeloftheconverterbasedonwhich the controller is designed. The other way is the artificialintelligencewayofusinghumanexperienceindecisionmaking.Amongthevarioustechniquesofartificialintelligence, the most popular and widely used technique incontrolsystemsisthefuzzylogic.Suchanintelligentcontroller designed may even work well with a system with anapproximatemodel.

Severalresearchershavecontributedinevolvingsuchintelligent controllers for boost converters. The technique byTse et al [4] fuzzifies the error and change in error of theoutput voltageandtheSugenofuzzy system givesout thechangeindutyratio.Reference[5]usesaverysimilarMamdani system and compares the system with sliding modecontroland fixed tolerance method.

$$T_c(s) = K\frac{\frac{s}{W_z}+1}{s} \qquad (2)$$

Reference[6]suggestsarobustPIfuzzycontrollerthatpredictstheincrementaldutyratio.Reference[7]givesapractical implementation of a Mamdani type fuzzy controllerand [8] presents an analog fuzzy controller implementation.Reference [9] presents a tuned fuzzy controller for improvedperformance.All the papers mentioned above establish theeasydesign andimplementation offuzzycontrollers.

Although several researchers have established the superiorperformance of the fuzzy controllers over linear controllers forseveral other non-linear plants, the boost converter is a uniqueplant due to its switching nature and presence of RHP zerowhichcomplicatesthecontrolproblem.TheperformancecomparisonbetweenfuzzycontrollerandthelinearPIcontroller in the operating range of the converter has so far notbeen demonstrated. This paper aims to establish the superiorperformanceoffuzzycontrollersovertheconventionalPIcontrollers at various operating points of the boost converter.Simulationresultsareshownandsettlingtimeandpeakovershoothave been used tomeasure the performance.

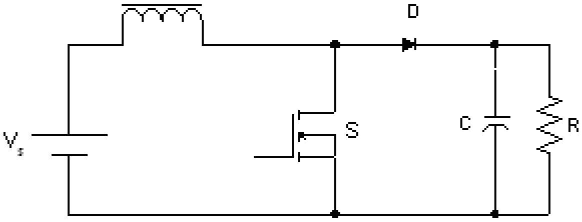


Fig. 1 boost converter

II. LINEARCONTROLLERS–DESIGNGUIDELINES

Thefrequencydomainmethodofdesigningclosedloopconverters involves several well-known steps. The followingsection lists outthese steps.

In boost converters, the presence of right-half-plane zeroforces the designer to go for low bandwidths to satisfy theaboverequirements.UsuallyaPIcontrolleroftransferfunction given by(2) is used.

A. Derivingthe smallsignalmodelofthe converter

The boost converter in Fig. 1,.when operating in continuousconductionmode,switchesbetweenthesetwo linear states, depending on the state of the switch ‘S'. The firststep in the design of controller for such a bi-linear system is toobtain its control-to-output transfer function. Using the statespaceaveragingtechnique,thecontrol-to-outputtransferfunctionoftheclassicalboostconverteroperatingin continuous conduction mode can be obtained as in (1). Thetransfer function shows a right-half-plane zero, which moveswiththe operating pointin the s-plane.

$$\frac{V_o(s)}{D(s)}=\frac{V_s}{(1-D)^2}\frac{\left(1-s\frac{L}{R(1-D)^2}\right)}{1+s\frac{L}{R(1-D)^2}+s^2\frac{LC}{(1-D)^2}} \qquad (1)$$

It can be seen from (1) that the control-to-output transferfunction is dependent on the operating point and its validity islimited to in and around the operating point. As the operatingregionoftheconverteriswide,theconventionalwayofdesigningthecontrollersinvolvesselectingtheworstcaseoperatingpoint i.e. under the minimum line and maximumload conditions.The transfer function of the converter underthe worst case conditions is taken as the base in the design ofthecontroller.

B. Controlrequirements

Thecontrolspecifications of the converter are

1. steadystateerror
2. settling timeand allowabletransientovershoot

In frequency domain terms, the steady state error is relatedto the dc loop gain. Thus the higher the open loop dc gain, thelowerwill be thesteady state error.

The settling time and transient overshoot are related to the 0dB crossover frequency of the loop gain and the phase margin.Systems with high crossover frequencies are much faster thanthe ones withlower crossover frequencies.

Thetransientovershootisrelatedtothephasemargin.Systems with low phase margins have higher peak overshootscompared to those with higher phase margins. A design withphase margin of 60 degrees will, typically, result in a transientovershoot of 1%.

C. Compensatorrequirements

Thecompensatorshouldensurethattheloopgainfrequencyplot

1. crosses 0dBat aslopeof -20dB/decade.
2. hasa phase marginclose to 60 degrees
3. has high dc gain

where W_z is the location of the controller zero and K is thegain of the controller. The controller has a pole at the origingiving a dc gain of infinity. As a result, it ensures zero steadystate error.

III. SIMULATEDBOOSTCONVERTER-SPECIFICATIONS

In order to compare the performance of the boost converterwith classical linear controller and with the fuzzy controller, a25V, 50 watts bench mark converter with the specificationsgiven inTable I has been considered.

TABLE I. CONVERTERS' SPECIFICATIONS

Input voltage	L	C	ESR of C	ESR of L	R
10-20 V	275 µH	540µF	0.015Ω	0.15Ω	12.5 to 100 Ω

The switching frequency of the converter is taken as 50 kHz.Forcomparison,fivedifferentoperatingpointsspanningtheentireoperatingrangeoftheconverterhavebeenselected.Correspondingtoeachoperatingpoint,a‘local'PIcontrollerthatgivesagoodperformanceisdesigned.Theperformanceoftheconverterwiththelocal PIcontrolleriscomparedwiththesingle‘universal'fuzzycontrollerusedatalltheoperatingpoints.

IV. UNIVERSALFUZZYCONTROLLER-DESIGNFORBOOSTCONVERTERS

The design of fuzzy controller needs a good knowledge ofthe system operation. The various steps involved in the designof fuzzy controllers for power converters are stated below. AuniversalSugenotypefuzzycontrollersimilartotheoneinhas been simulated for the boost converter specified inTable I.

A. Identification of inputsandoutputs

This step in the design identifies the key inputs that affectthe system performance. The goal of the designer is to ensurethattheoutputvoltagematchesthereferencevoltage.Theinputstothe fuzzycontroller are

1. Thevoltageerror(e)(referencevoltagesubtractedfromactualvoltage.)
2. Thechangeofthevoltageerror(ce)(previouserrorsubtracted fromcurrent error) over onesample period.

Some controllers may even use more information in theform of the inductor current [6]. The voltage error input issampledonce in every cycle.

Theoutputofthecontrolleristheincrementalcontrolaction i.e. theincremental duty ratio.

B. Fuzzifyingtheinputsandoutputs

The universe of discourse (range) of the inputs is dividedintoseveral fuzzy sets of desired shapes. The membershipfunctionsfor the inputs are shown in Fig. 2.

Outputsarealsomappedintoseveralfuzzyregionsofdesiredshapes(forMamdanitypesystem)orseveralsingletons(forSugenotypesystems).Forthisspecificproblem, output memberships are represented by 17 Sugenotypesingletons taking values between -1 to 1.

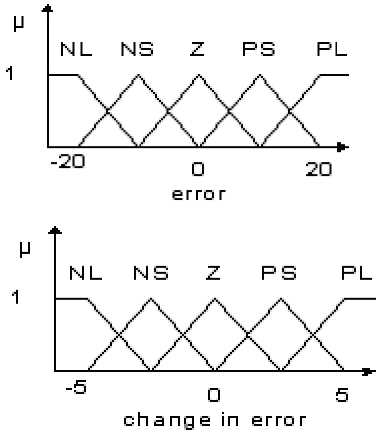


Fig.2.Membershipfunctionsforinputs

C. Development ofrulebase

Therulesconnectingtheinputs and the output singletonsare based on the understanding of the system.Normally thefuzzy rules have if...then… structure

The inputs are combined by AND operator. Rules that weredeveloped in the work are given in Table II.

TABLEII.RULETABLE

e ce	NL	NS	Z	PS	PL
NL	1	0.5	0.2	0	-0.3
NS	0.65	0.35	0.1	-0.1	-0.35
Z	0.45	0.2	0	-0.2	-0.45
PS	0.35	0.1	-0.1	-0.35	-0.65
PL	0.3	0	-0.2	-0.5	-1

D. Defuzzification

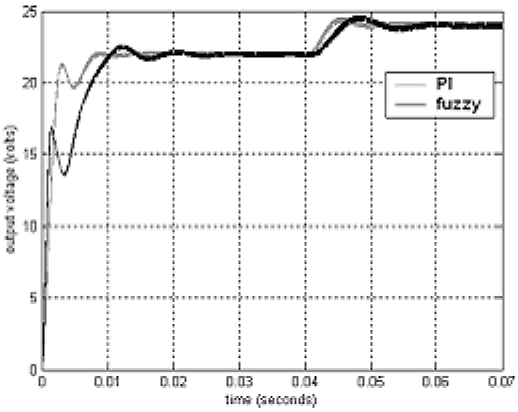
Theoutputspacewiththe‘fired'singletonsis‘defuzzified'to get a final ‘crisp' value of the incremental control. Severaldefuzzificationmethodsareavailable[10].Thecentreofgravitymethodisthemostcommonlyused method whichgives thedefuzzifed‘crisp' valueas

$$Z_o = \frac{\sum_{i=1}^{N} c_i * w_i}{\sum_{i=1}^{N} w_i} \qquad (3)$$

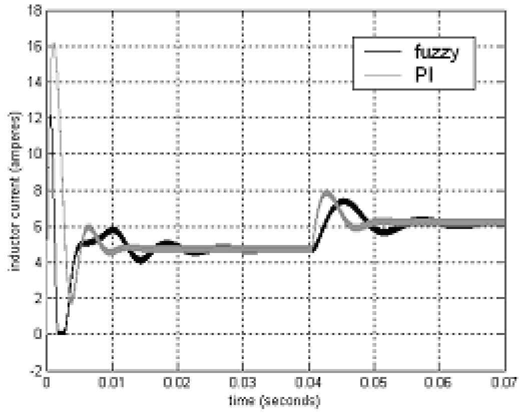
SIMULATIONRESULTS

Asstatedearlier,tocomparetheperformanceoftheconverterwiththefuzzycontrollerandtheonewiththeconventional PI controller, five operating points spanning theentireoperatingregionoftheconverter have been chosen.Thus the five different ‘local' PI controllers giving a goodperformance at the operating points have been designed. Theoperating points selected are listed below. V_o=25V in all thecases.

1. Minimum line and maximum load condition:V_s=10V, I_o=2 A.
2. Minimum line and light load condition:V_s=10V, I_o=0.5 A.
3. Midrange line and load condition:V_s=15V, I_o=1A.
4. Maximum line and maximum load condition:V_s=20V, I_o=2A.
5. Maximum line and light load condition:V_s=20V, I_o=0.5A.



(a)



(b)

where‘w_i' is the membershipvalue ofthe output set ‘i', ‘c_i'is the corresponding singleton value, and ‘N' is the number ofoutputsingletons.Thedefuzzifiedvalue‘Z_o'ismultipliedbya gain [4] to get the incremental duty ratio. The lower gainhelps in reducing the oscillations of the fuzzy controller butgivesaslowerresponse.Highergainsmakethecontrolleroscillatory.

Fig.3.ComparisonofstartupandstepuptransientatV$_s$=10V,I$_o$=2A, Vref=22V,stepfrom22Vto24Vatt=40ms
(a)outputvoltage(b)inductorcurrent.

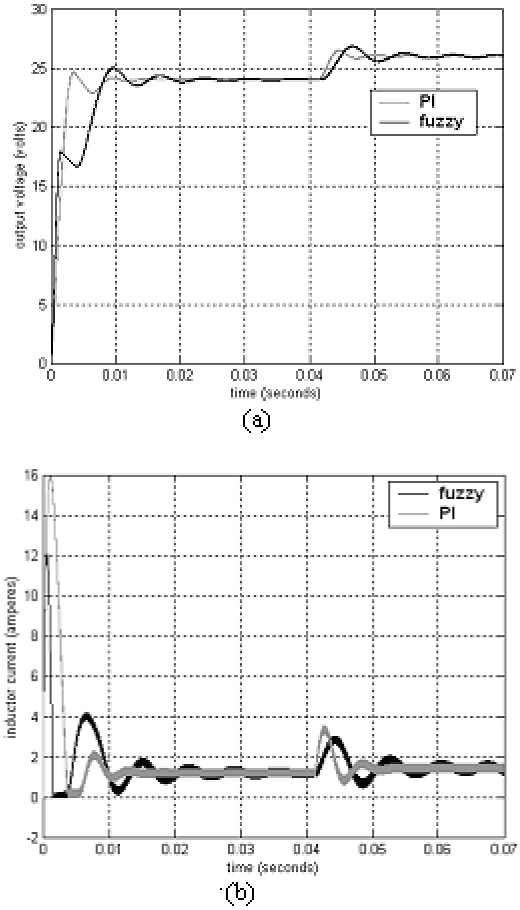


Fig.4.Comparisonofstartupandstep uptransientatV$_s$=10V,I$_o$=0.5A, Vref=24Vforstartup,stepofVreffrom24Vto26Vatt=41ms
(a) outputvoltage(b)inductorcurrent

A. Case1:Minimumline andmaximumloadedcondition(Vs=10V, Io=2A)

PIcontrollerdesigned: $$T_c(s)=17.25\frac{\frac{s}{853}+1}{s} \quad (4)$$

Phase margin achieved: 46.489 degreesGain crossoverfrequency: 461.39 rad/s.

Fig.3showsthestartupandthesmallsignalsteptransientofthe converter withthe fuzzyand PI controllers.

For large signal transient, the settling time is taken as thetime taken by the response to reach and stay within 3% of thedesired value. For small signal transient, the settling time istakenasthetimetakenbytheresponsetoreachandstaywithin5% of the desired output.

Theresponseforlargesignaltransientinallthecaseshas aninitialovershootthatcorrespondstotherapidbuildingup

B.Case 2: Minimum line and light loaded condition(Vs=10V, Io=0.5A)

Fig.4showsthelargesignalstartupandthesmallsignalstep response of the converter with the controllers. The PIcontrollerdesignedinthiscaseis given in (5). The phasemargin of the loop gain is 45.3 degrees and the crossoverfrequencyis 981 rad/s.

$$T_c(s)=17.25\frac{\frac{s}{1004}+1}{s} \quad (5)$$

The resultsaretabulated inTableIII andTableIV

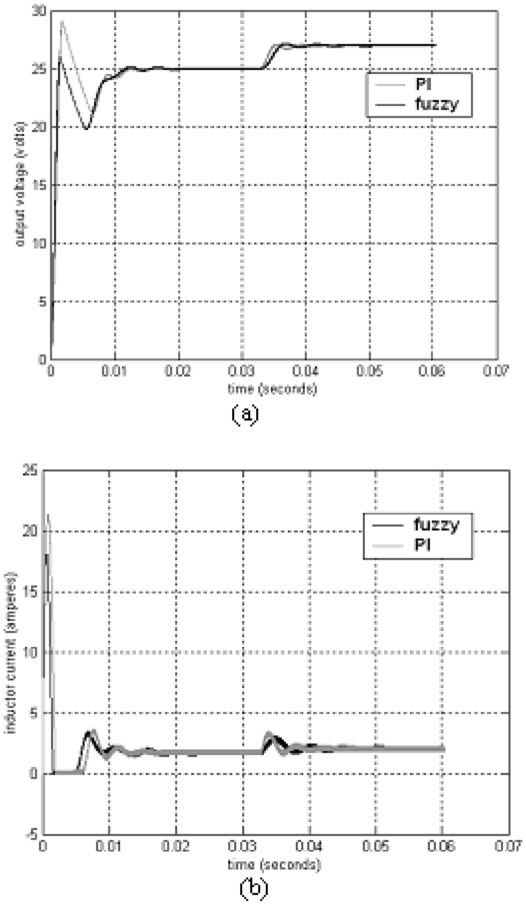


Fig.5.ComparisonofstartupandstepuptransientatV$_s$=15V,I$_o$=1A, Vref=25Vforstartup,stepofVreffrom25Vto27Vatt=33ms
(a)outputvoltage(b)inductorcurrent.

C. Case 3:Midrangelineandhalfloadedcondition(Vs=15VIo= 1A):

$$\frac{s}{}+1$$

ofcurrentintheinductorandtheinitialchargingofthe unchargedcapacitor.Toavoidovercurrents,usuallythecircuit has a startup mechanism that slows down the startupprocess.

Theperformanceresultsoftheconverterundertheminimum line and maximum load conditions are tabulated inTable III and Table IV.

Phase margin achieved: 80.96
degreesCrossover
frequency:943.5 rad/s

Fig. 5 shows the startup and small signal transients of theconverterwiththecontrollers.Thefinalresultsaretabulate din Table III and Table IV.

PIcontrollerdesigned: $T_c(s)=16.5\frac{1517}{s}$ (6)

D. Case4:Maximumlineandmaximumloadedcondition(Vs =20VIo=2A):

$$\text{PIcontrollerdesigned:}T_c(s)=22\frac{\frac{s}{2027}+1}{s} \qquad (7)$$

Phase margin achieved: 96.4665 degreesCrossover frequency:781 rad/s

Fig.6showsthestartupandthesmallsignalsteptransientof the converter with the two controllers. The overshoots aremuchhigherwithboththecontrollersforstartup,butthesettling time is small for the fuzzy controller. The results aretabulated in Table III and Table IV.

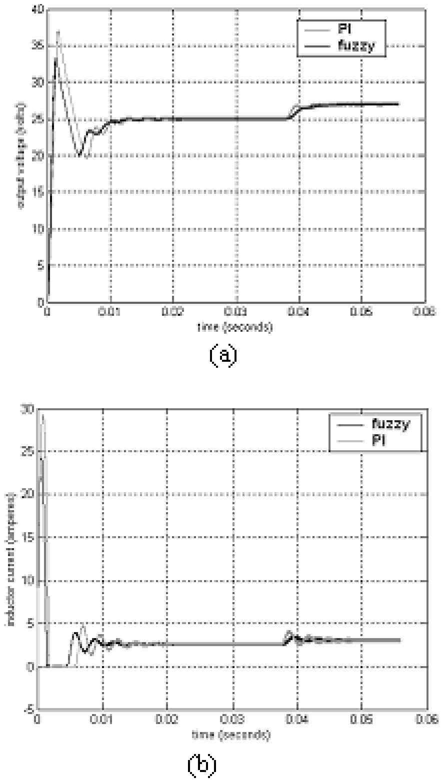


Fig.6.ComparisonofstartupandstepuptransientatV$_s$=20V,I$_o$=2A, Vref=25Vforstartup,stepofVreffrom25Vto27Vatt=38ms (a)outputvoltage(b)inductorcurrent

E. Case5: Maximumlineandlightloadedcondition(Vs=20V,Io=0. 5A):

$$\text{PIcontrollerdesigned:}T_c(s)=20\frac{\frac{s}{2058}+1}{s} \qquad (8)$$

Phase margin achieved: 99.234 degreesCrossover frequency: 731 rad/s.

Fig. 7 shows the startup and small signal transients of theconverter with the controllers. The fuzzy controller is having amuchsuperiorperformanceforthelargesignalstartuptransient and a comparatively better performance for the smallsignaltransient.

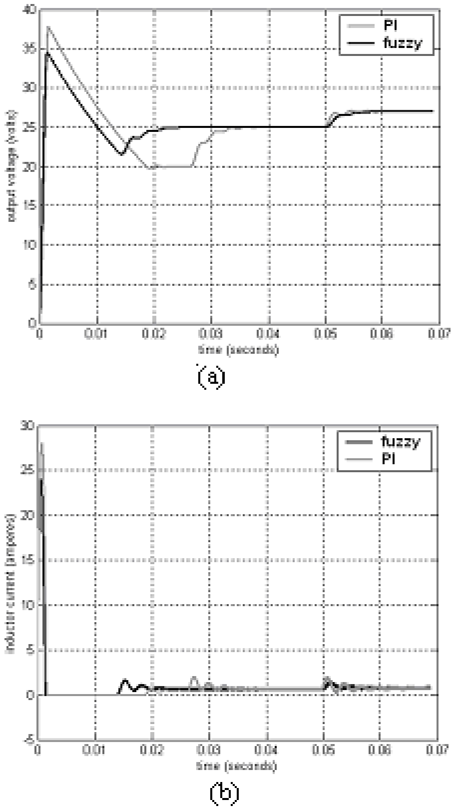


Fig.7.Comparisonofstartup andstepuptransientatV$_s$=20V,I$_o$=0.5A, Vref=25Vforstartup,stepofVreffrom25Vto27Vatt=49ms (a)outputvoltage(b)inductorcurrent.

.

TABLEIII.STARTUPTRANSIENT-COMPARISON

Case	V_s (V)	I_o(A)	V_{ref} (V)	startuptransient			
				startup transientsettlingtime(ms)		% overshootof outputvoltage	
				fuzzy	PI	fuzzy	PI
1	10	2	22	10	7.5	2	<1%
2	10	0.5	24	11	8	3.75	3.75
3	15	1	25	10.5	11	4	16
4	20	2	25	33	37	40	48

TABLEIV.STEPRESPONSE-COMPARISON

Case	V_s (V)	I_o(A)	stepresponse(V)		stepresponse			
					settling time(within 5% ofthe reference)(ms)		% overshoot	
			From	To	fuzzy	PI	fuzzy	PI
1	10	2	22	24	13	7	3.04	2
2	10	0.5	24	26	40	10	2.88	1.92
3	15	1	25	27	8.5	6	0.55	0.185
4	20	2	25	27	5.5	7	0.148	0.37

TableIIIgivesthecomparisonofthestartuptransient.

settlingtimeandpercentageovershootandTableIVcompares thestep response transients

Fromthesimulationresults,thefollowingconclusionscanbemade
.

1. Ingeneral,thefuzzycontrollergivessmallovershootsforlargesignaltransientsandhasamuchsuperior

largesignalperformancecomparedtothelocalPIcontrollers (Table III, Cases 3, 4,& 5).

2. Thefuzzycontrollermatchestheperformanceof thePIcontrollersforsmallsignaltransientsathigherinputvoltages(TableIV,Cases3,4,&5).ThesuperiorperformanceofthePIcontrollersinsomecasesisdueto localoptimizationofthecontroller.
3. As stated earlier, the fuzzy controller has the tendencyto oscillate around the final operating (settling) point.The oscillations also depend on the system's parasiticelements,namelytheinductorresistanceandtheswitchresistance.Theoscillationsarelessiftheparasiticresistors are high.

A decrease inoscillations can be achieved by reducingthe gain of the fuzzy controller, or by making the controllerinsensitive around the final settling point. Selection of thenormalizing gains for the inputs for avoiding oscillations isdiscussed in[15].

V. UNIVERSALFUZZYVERSUSUNIVERSALPICONTROLLER

Asstatedearlier,the“universal”PIcontrollerfortheconverterisdesignedundertheworstcaseconditionsofminimumline(V_s=10V) andmaximumload(I_o=2A)(givenby (4)). The performance of the universal fuzzy controller andthat of the universal PI controller under the maximum line(V_s=20V) and light loaded (I_o=0.5 A) conditions are tabulatedin Table V.

TABLEV.UNIVERSALFUZZYVERSUSUNIVERSALPI

Controller	Startup transient forVref=25V, Vs=20V,I_o=0.5A		Smallsignalstepfrom25 Vto 27V	
	settling time(ms)	percentage overshot	settling time (ms)	percentage overshoot
Fuzzy	19	38	7	0
PI	36.5	56	8.5	0

Thus it can be concluded that the universal fuzzy controllermatchestheperformanceofthelocalPIcontrollersanditexhibitssuperiorperformanceoverthe“universal”PIcontrollerstypicallyused in the powerconverters.

Theuniversalfuzzycontrollerfortheboostconvertercanbeimplementedwithdigitalsignalprocessors[4]orwithmicrocontrollers[7].

VI. CONCLUSION

From the simulations results, it can be concluded that theproblem of dynamics in boost converter due to the right-half-plane zero can be handled by a fuzzy controller. The fuzzycontrollerbehaveseffectivelylikeatunedlocalcontrollerdesignedforeachoperatingpointandgivesanimprovedperformance compared to the conventional low bandwidth PIcontrollersused.Simulationresultspresentedinthis paperestablishthesuperiorityofthefuzzycontrollerovertheclassical PI controller.

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