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Digital State Feedback Current Control using the Pole Placement Technique

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ABSTRACT

A digital state feedbackcontrol method for the current mode control of DC-DC converters is proposed in this paper.Thisapproachcanpreciselyachieveinterleavedcurrentsharingamongtheconvertermodules.Asthe controllerdesignand system analysis are performed in the time domain, the proposed method can easily satisfy the required converterspecification by using the pole placement technique. The digital state feedback controller in the continuous and discretetime domain is derived for the robust tracking control. For the verification of the proposed control scheme, a parallelmodulebi-directionalconverterinaprototype42V/14Vhybridautomotivepowersystem,whichisadesignexamplein the continuous time domain, and a parallel module buck converter, which is a design example in the discrete time domain,areimplementedusing aTMS320F2812digitalsignalprocessor(DSP).

Keywords: digitalcontrolofDC-DCconverters,digitalstatefeedbackcontrol,poleplacementtechnique,parallelinterleaved current

INTRODUCTION

Everincreasingdemandsforthedevelopmentofcompact,lightweightpowersupplieswithmorepowerdensity, higher efficiency and fast dynamics often requirepowerconversionthroughparallelconnectedconverters.In order to achieve the current sharing among the modules,various analog current mode control methods such as peakcurrentmodecontrol,chargecurrentmodecontrol,averagecurrentmode control,etc., areused. Withrecentadvancesindigitalsystems,digitalcontrol

has become increasingly visible even for high frequency,low-to-mediumpowerswitchingconverters.Digitalcontroloffersthepotentialadvantagesofimmunitytoanalogcomponentvariations,programmabilityandpossibilities to improve performance using more advancedandsophisticatedcontrolalgorithms[1-5].

However, a direct digital implementation of the analogcurrent mode control is not easy. In analog current modecontrol, the switch current or the inductor current is sensed,and the switch duty cycles of each converter module aregenerated by comparing the sensed current to a reference.Because the switch or inductor current is a fast changingwaveform with a high switching frequency, the need for avery fast analog to digital converter (ADC) to producemultiplesamplesofthesensedcurrentperswitchingperiod,andthecorrespondingneedforthelargesignal processing capabilities, may require excessively complexhardware.Thus,a digitalcurrentmodecontrolmethodthat can match or exceed the performance of the standardanalog current mode control has been of much interest. In[4, 5], current estimated algorithms are proposed. Thesealgorithms focus on the current mode control to improvethe dynamics. Even though the dynamicsare improved,the current sharing among the parallel converter modulescannotbesolved.Furthermore,aparallelinterleavedconverter control method using the sliding mode controlwasproposed[3].However,thiscontrollerdesigntechniqueisverycomplexandtheexpansionofthemodulesis notconvenient.

experimental results from two 100W parallel module buckconvertersarepresented.Conclusionsofthepaperarepresentedinthe lastSection.

1. Robust Tracking Control using the PolePlacementTechnique

Thestatefeedbackcontrollerstructureinthecontinuoustimedomain

Most switching converters operating in the continuousconduction mode (CCM) have two state equations withinoneswitchingperiodasfollows;

In this paper, a digital state feedback control method forthe current mode control is proposed in the continuous anddiscretetimedomains.Thisapproachcanprecisely

$\dot{x}(t) = A_1 x(t) + b_{vg1} v_g(t) + b_{io1} i_o(t),$

$\dot{x}(t) = A_2 x(t) + b_{vg2} v_g(t) + b_{io2} i_o(t),$

$nT_s \le t \le (n + d)T_s$

$(n + d)T_s \le t \le (n + 1)T_s$

(1)

achievethe interleaved current sharing among the

where,

$x(t)$

isastatevector,

$v_g(t)$

isaninputvoltage,

converter modules. Also, the required converter

$i_o(t)$

isanoutputcurrent,

$d(t)$

isadutyratioandT_s is

performance,suchasthesettlingtimeandmaximumovershoot of the step load response, can be easily satisfiedbecausethecontrollerdesignandsystemanalysisusingthe pole placement technique are performed in the timedomain[6].Fortheverificationoftheproposedcontrol

aswitchingperiod.Fromthecontinuousdifferentialequation (1), the average continuous time state equationcanbederivedforthecontinuousstatefeedbackcontroller.

scheme,aparallelmodulebi-directionalconverterina

$\dot{x}(t) = A_c x(t) + B_c d(t) + B_{vgc} v_g(t) + B_{ioc} i_o(t),$

y(t) C$_c$x(t)

prototype42V/14Vhybridautomotivepowersystem,which is a design example in the continuous time domain,alongwithaparallelmodulebuckconverter,whichisa

where

A_C DA_1 $D'A_2$

B_C A_1 A_2 X B_{vg1} B_{vg2} V_g B_{io1} B_{io2} I_o

B_{vgc} DB_{vg1} $D'B_{vg2}$

(2)

designexampleinthediscretetimedomain,isimplementedusingaTMS320F2812digitalsignal

B_{ioc}

DB_{io1}

\+ $D'B_{io2}$

processor(DSP).

where,

X,D,V_g

and

I_o arethesteadystatevalues

Thispaperisorganizedasfollows.InSection2,thestatefeedbackcontrollerusingthepoleplacementtechnique isderivedforthe robusttracking control. InSection3,afterreviewingthelimitationofthebi-directional DC-DC converter using an analog controlscheme, the proposed current mode control to overcometheseproblemsisdiscussedforacontrollerdesign

of the state, duty ratio, input voltage and output current,respectively. The objective is to design an overall systemsuchthattheoutput y(t) willtrack,asymptotically,any

stepreferenceinput,r(t) R (constant) ,evenwiththepresence of an input disturbance and with plant parametervariations.Letanerrorstate,e(t),andaugmentedstate

examplein the continuous time domain. For the

variables,

z(t),

u(t),

w(t),bedefined,andassumethat

verificationofthetheoreticalanalysis,aparallelmodule

theinputvoltage,

v_g,andoutputcurrent,

i_o,are

bi-directionalconverterinaprototype42V/14VhybridautomotivepowersystemisimplementedinSection4.In

sustainedandslowlyvarying.

Section5,foradesignexampleinthediscretetime

e(t) r(t) y(t),

z(t) x(t),

u(t) d(t)

domain,aparallelmodulecurrentcontrolschemeforthe

e(t) r(t) y(t) C_cx(t) C_cz(t)

(3)

buckconverterwasdesignedandsimulated.Also,the

$w_1(t) = \hat{v}_g(t) = 0,$

$w_2(t) = \hat{i}_o(t) = 0$

Then,thesystemcanbeexpandedbytheaugmented statevector e(t) z(t)^T.

2.2Thestatefeedbackcontrollerstructurein thediscretetimedomain

Fromthecontinuousdifferentialequation(1),the

$\dot{e}(t)$

0 C e(t)

c

0

e(t)

averagediscretetimestateequationcanbederivedforthe

$\dot{z}(t)$

0

A

z(t)

B

u(t),

$u(t) = K_1$ K_2 z(t)

discretestatefeedbackcontroller[11].

c

c

()

$x(k+1) = A_z x(k) + B_z d(k) + B_{vgz} v_g(k) + B_{ioz} i_o(k)$

$y(k) = C_z x(k)$

$v_g(t)$

$i_o(t)$

where $A = \exp(ADT)\exp(AD'T)$

(7)

$B_z = A_z (A_1 - A_2) X + (B_{vg1} - B_{vg2}) V_g + (B_{io1} - B_{io2}) I_o$

$B_{vgz} = (DB_{vg1} + D'B_{vg2}) T_s,\ B_{ioz} = (DB_{io1} + D'B_{io2}) T_s$

z 1 s 2 s

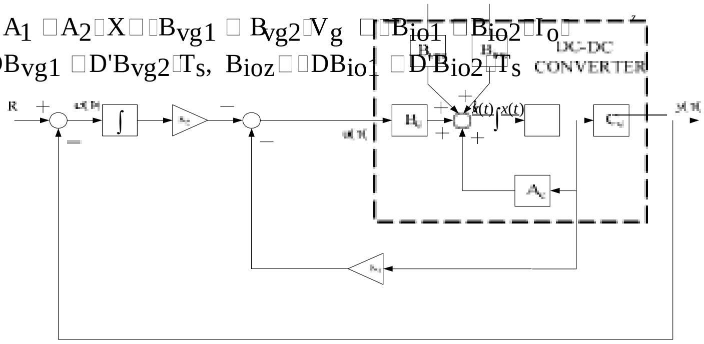
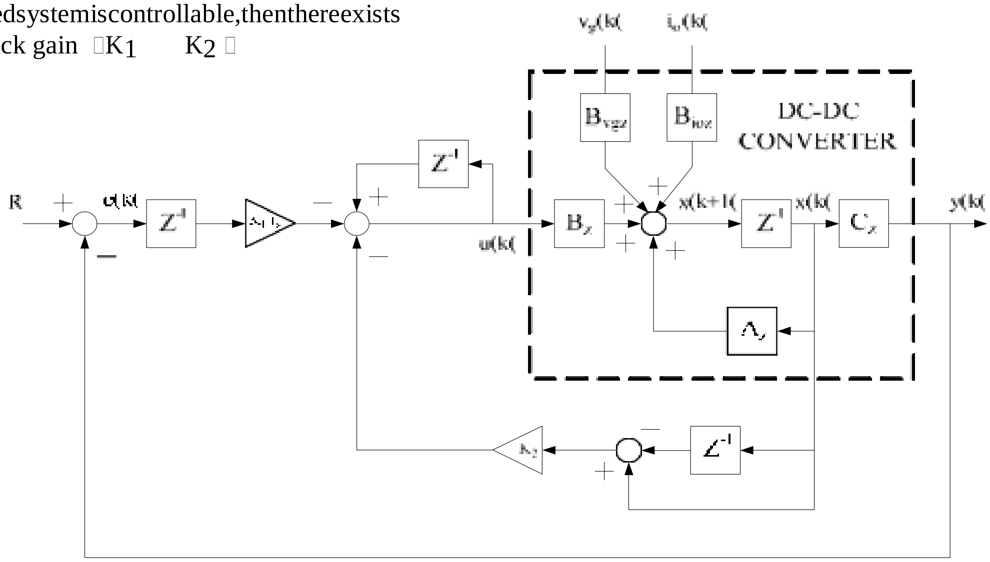


Fig. 1The continuous state feedback controller scheme for therobust trackingcontrol

Iftheexpandedsystemiscontrollable,thenthereexists
a statefeedback gain K_1 K_2



suchthattheexpanded
system is stable. That means the output of the converterstracks the reference value. Furthermore, using the statefeedbackgain,thesystem'seigenvaluescanbeplacedto
thedesiredpoles,whichdeterminetheperformanceofthe
Fig. 2The discrete state feedback controller scheme for therobust trackingcontrol

Theobjectiveistodesignanoverallsystemsuchthat
feedbackcontrolsystem.Fig.1showstheoverallclosed
theoutput
y(k)
willtrackasymptoticallyanystep
loopsystemusingthecontinuousstatefeedbackcontrol.Thedutyratiocanbederivedfromequation(3)and(4)as
referenceinput,r(k) R(constant),evenwiththepresenceofaninputdisturbanceandwithplantparameter
follows;
variations.Letanerrorstate,
e(k),andaugmentedstate
variable,z(k),u(k),w(k),bedefined,andassumethatthe
d(t) u( )d K e( )d Kx(t)
(5)
inputvoltage,
v_g,andoutputcurrent,
i_o,aresustained

Sincethecontrolinputisthedutyratio,themagnitudeofthecontrolinputmustbecheckedbecauseofits andslowlyvarying.

e(k)□r(k)□y(k)□ R□ C(k),z(k)□x(k)□ x(k□1)□x(k)

z

boundaryconstraint.Thiscanbeeasilycheckedfromthe Ts
allowedmaximumdutyratio,theswitchingfrequency,the

u(k)□d(k)□ d(k□1)□ d(k) , e(k)□□C z(k)
(8)
z

T

designedfeedback gain and the required system s
specification,asfollows;

w1(k)□vg(k)□0, w2(k)□io(k)□ 0 usingEuler'smethod

u(t)□d(t)□K1e(t)

max
+ K2z(t)

max
Fromasimilarprocedureinthecontinuoustimecase,
D □ D
(6)
thestateequationoftheoverallclosedloopsystemis
□ KR□ Kx(t)
□ max min

1 2 spec *T*
s
givenasfllows

e(k 1) 1
=
z(k 1) 0
 TsCz e(k) 0 u(k)
A z(k) B
components.Fig.4showsthetypicalanalogcontrolschemeofthe42V/14Vbi-directionalDC-DCconverter,

z z
(9)
u(k) K1
e(k)
2 z(k)]*K*
whichusuallyisrealizedwithgeneralpurposePWMICs
forswitchmodepowersupplies.SincethesePWMICsare

unabletochangetheroleofthetwoswitchesin
d(k) d(k 1) KTe(k 1) K x(k) x(k 1)
(10) 1 s 2
synchronousbuck/boostoperation,itisgeneralpracticeto

u(k) d(k) K1e(k)max K2z(k)max
D D

(11)
 KR Kx(k) *T* 14V
 max
min
42V
1 2 spec
s

Duty

Fig.2showstheoverallclosedloopsystemusingthediscretestatefeedback control.

2. The 42V/14V Bi-Directional DC-DCConverterApplicationfortheContinuous TimeDomainDesignExample

Fig. 4The typical analog control scheme of the 42V/14Vbi-directionalDC-DCconverter

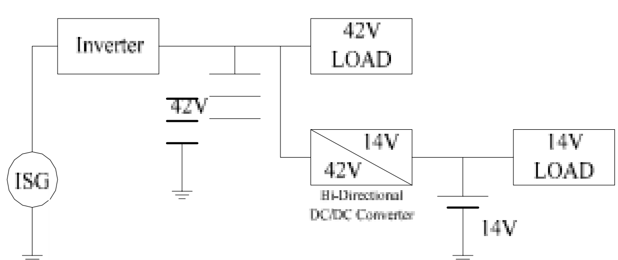


Fig.3Thedualbattery42V/14V system

Problemsoftheconventionalanalogcontrolscheme

The42V/14Vdualvoltagesystemshavebeenadoptedtoprovidebackwardcompatibilitywiththeexistingcomponents of the 14V system [7]. Fig. 3 shows one of thepopular architectures for implementing the 42V/14V dualvoltage system. Two batteries are connected to a 42V busanda14Vbus,respectivelyandbi-directionalDC-DCconverter allows the power to be exchanged between thetwobuses.

When implementing a 42V/14V DC-DC converter, asimple non-isolated buck or boost converter is sufficient,since isolation between the two buses is not required inautomobiles.Asynchronousbuck/boosttopologyisconsideredtobemoreattractivesincebi-directionaloperationispossiblewithouttheneedforadditional

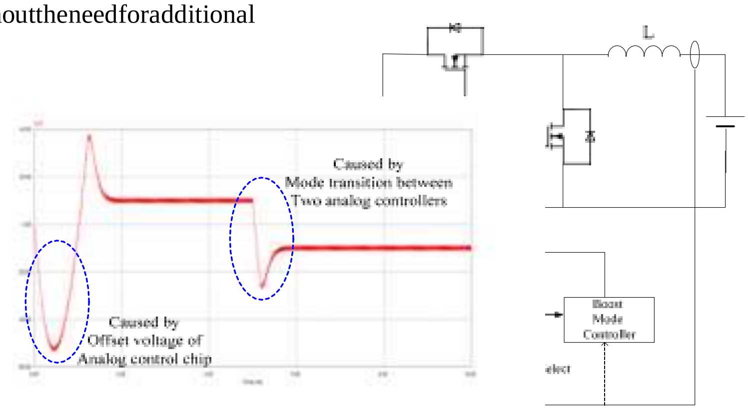


Fig. 5The transient current simulation results of the analogcontrolscheme

haveaseparatecontrollerforeachoperationmode.Additionally,thePWMICshaveasoft-startfunctionanda voltage offset to increase the switching duty ratio slowlyat the starting time and to allow for noise margin [10]. Dueto these reasons, the transient current of the synchronousbuck/boost converter may flow as shown in Fig. 5. Thisphenomenon,whichiscausedbythesaturationoftheerrorampoutputofthedisabledcontroller,maybeobserved during startup and in mode transitions as well [8,9]. However, the proposed digital control scheme does nothave these transient problems. Thus, the system's stabilityanddynamics are additionallyimproved.

Theproposedcontinuousstatefeedbackcontrolscheme

Settlingtime□

4

□ □n

□1mS,

P.O.□ 100e□ □ □/

□1%

$\sqrt{1-\xi^2}$

(14)

AsshowninFig.6,thebi-directionalconvertermodulehasonlyonestatevariable,theinductorcurrent.Usingthe un-terminatedmodelingmethod,thestateequationis

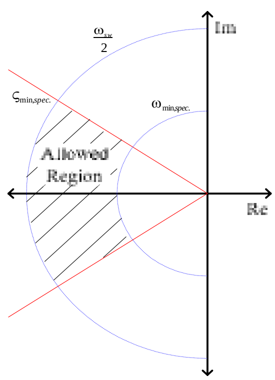
□ □ s^2□ 2□ □

  2 ,

  sw(Singularpoint)
n 2

derivedas
SWON)i
1v
L L42
1v
L14
,SWOFF)i
  1v
L L14
(12)
Fig. 7 shows theallowed region of the desired polelocation.Usingthispoleplacementtechnique,thecontinuousfeedbackcontrollerforthesystemcanbedesigned.
Toverifythetheoreticalanalysis,theproposeddigital
FromthesameprocedureinSection2.1,thestateequationoftheoverallclosedloopsystem isgivenasfollows;
state feedback control scheme has been tested by using theMATLABSimulinksoftware.Thesynchronousbuck/boostconverterparameterschosenforthissimulationare:

e(t) 0
&KV
 1= e(t)
KV
 z(t)



1 42
2 42 z(t)
L
L

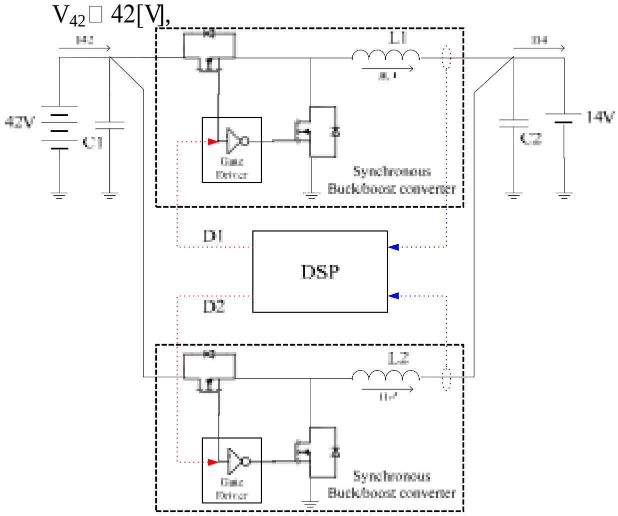
(13)

$$\square\ \square\ s^2 \square \frac{K_2V_{42}}{L} s \square \frac{K_2V_{42}}{L} \square\ 0$$

Theaugmentedsystemisasecondordersystem.Therefore,thedesiredpolelocationscanbeeasilyobtainedfromthegiven converterspecificationandthe

Fig.7Therootlocusforthepole placement

$V_{42} \square$ 42[V],



$V_{14} \square$ 14[V],

$L_1 \square$ 11[□ H],

$r_{L1} \square$ 30[m□],

$L_2 \square$ 9[□ H],

$r_{L2} \square$ 50[m□] ,and

$F_{SW} \square$ 100[kHz]where

$r_{L1,2}$

istheESRoftheinductor.

$C_{1,2}$

isneglectedinthis

simulation.Fromequation(14),thefeedbackgainis

designedas

$K_1 \square\ \square$ 23.0895,

$K_2 \square$ 0.0047(where

□ □ 0.99,

$\square_n \square$ 10k).When$\square_n$

isselected,thedigitalsampling

Fig. 6The parallel interleaved bi-directional converter controlscheme

effectshouldbeconsideredbecausethecontrollerisrealizedin aDSP.

Fig. 8 shows the current response during startup andtransitionfrombuckmodeoperationtoboostmodeoperation.Theproposeddigitalcontrolschemehasasmoothtransitionbetweenthetwomodesbecausethecurrent controller canoperate for the positive and negative

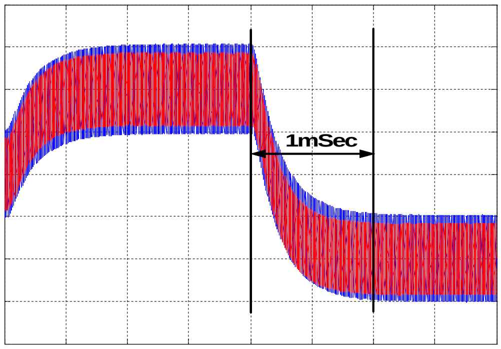
generalsecondordersystem'sresponse.Letthegiven

converterspecificationsbedefinedasfollows;settlingtime□ 1mS,P.O.□ 1%.From therequired

systemdynamics,thecharacteristicequationofthedesiredpolesisgivenby

reference,andcaneasilyachievetherequireddynamicsfor the given specification because time domain analysis isused.Also,itisobservedthattheinterleavedcurrentsharingamongtheconvertermodulesispreciselyachieved.

20



15

10

Current[A] 5

0

-5

-10

-15

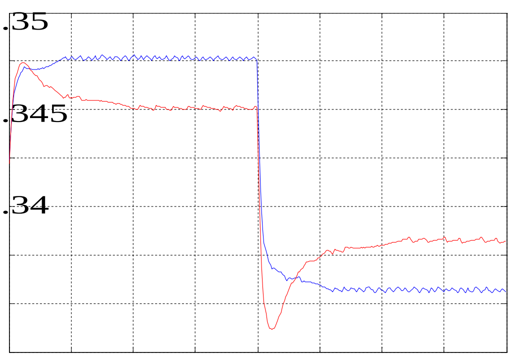
-20

InductorcurrentofEachmodule

TheproposedcontrolschemeisrealizedusingaTITMS320F2812 32bit fixed point DSP, which has a 12bitADC,16bitPWM,150MIPSperformance,etc.Fig.9depictsthePWMdutyratiogenerationandtheexactsamplingf requencygenerationusingthesynchronousPWM as well as the average inductor current samplingmethod without the use of a filter. Also, this PWM schemecan easily generate two phase shifted duty cycles by usingthepeakandvalleyofthePWMcounter.Takinginto
accountthe A/D conversion time and the control

0 0.5 1 1.5 2 2.5 3 3.5 4

0.35



0.345

0.34

Time[Sec]

DutyRatioofEachmodule

$x10^{-3}$

algorithm calculation time, the duty cycle is updated at thenext sampling time. This provision reduces control delaysin thefeedback loop.

The prototype hardware, which consists of two parallelbuck/boostconvertermodules,isbuiltasshowninFig.6.

Dutyratio

0.335

Theconverterparametersare:

C_1 □ C_2 □ 300[□ F],

L_1 □ L_2

0.33

□ 10[□ H]

and

F_{SW} □ 100[kHz].A36VbatterymadebyGS

0.325

0.32

0.315

0 0.5 1 1.5 2 2.5 3 3.5 4

of Japan and a 12V battery made inKorea are used. Fig.10 shows the experimental result of the inductor currentduring startup transition. It is observed that there is notransientcurrentflow,asshowninFig.5.Fig.11and12

Time[Sec]

$x10^{-3}$

showthecurrentresponseduringthetransitionfrombuck

Fig. 8The simulation results of the proposed digital statefeedbackcurrentcontrol

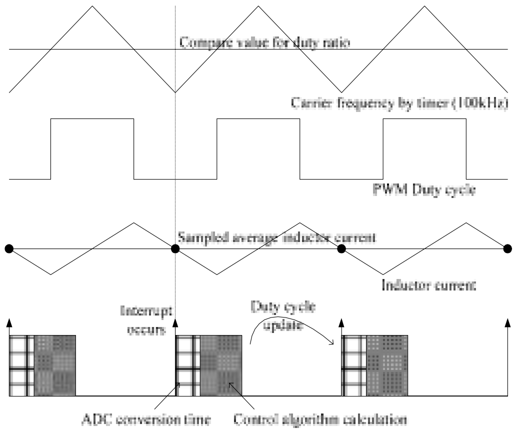


Fig.9TheDSPcontrolstrategy

3. ExperimentalResultsoftheBi-DirectionalConverter

mode operation of 20[A], corresponding to 10[A] for eachmodule, to boost mode operation of -20[A], and vise versa.Theinterleavedcurrentsharingispossibleduringthetransient period, as well as in steady state. The responsetime is in good agreement with the simulation results andthusthe theoretical analysis is confirmed.

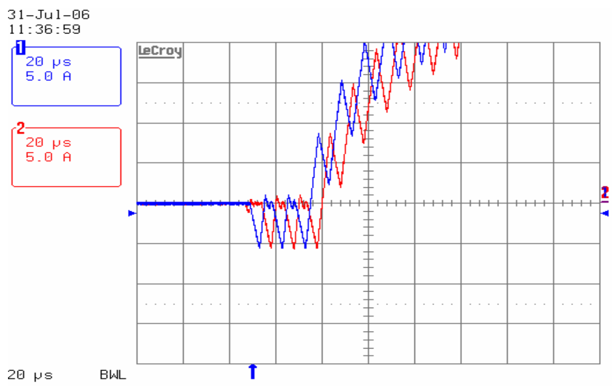
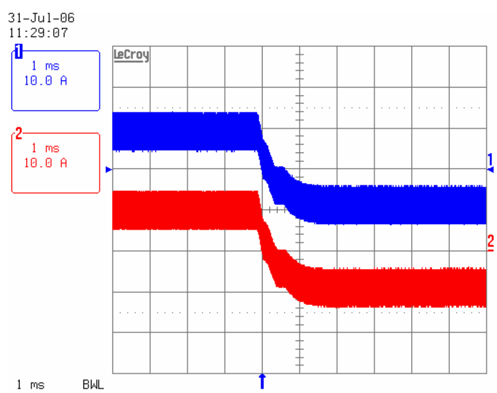


Fig.10The startuptransitiontobuck modeoperation

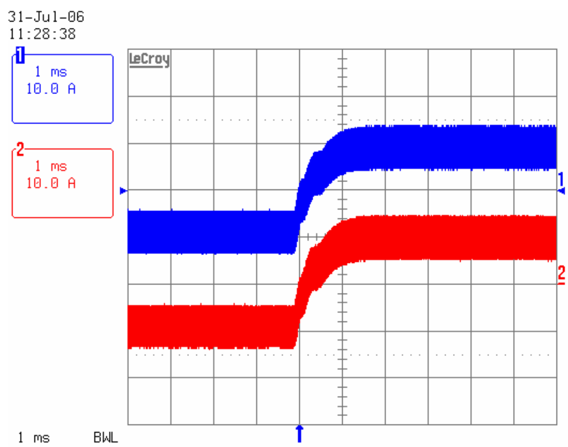


The proposed discrete state feedback control scheme forthe buck converter is illustrated in Fig. 13. Using the un-terminated modeling method, the state equation is derivedas

SWON)i
 1 v 1 v,SWOFF)i 1 v
(15)
L L g L o L L o

Fig.11Themodetransitionfrombucktoboostmodeoperation

FromsameprocedureinSection2.2,thestateequationoftheoverallclosedloopsystemisgivenasfollows;
e(k 1) 1
 T_s
 e(k)
K $_1$ V $_g$
K $_2$ V $_g$
(16)
z(k 1)



 T_s 1
 L
L T_s z(k)

Theaugmentedsystemisasecondordersystem.Therefore, the desired pole location can be easily obtainedfromthegivenconverterspecification,aswellasthegeneralsecondordersystem'sresponseusingthecontinuous and discrete time domain relationship. Let thegivenconverterspecificationsbedefinedasfollows;Settlingtime 100 S,P.O. 1%.Fromtherequired systemdynamics,thedesiredpolelocationsaregivenby

Fig.12Themodetransitionfromboosttobuckmodeoperation

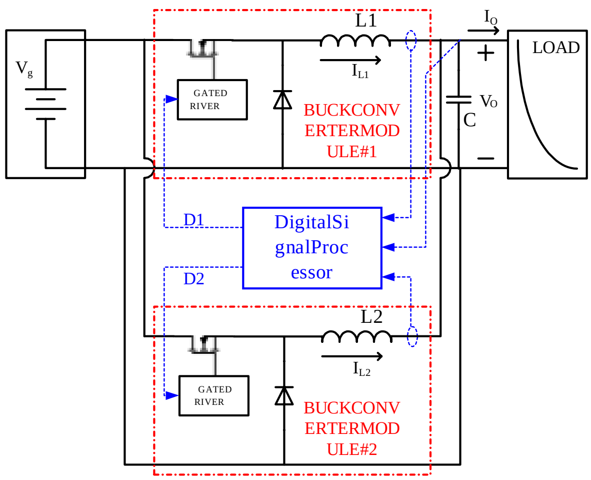
Settlingtime□$\frac{4T_s}{}$□ 100□ S,
ln(r)
P.O.□ 100e$^{□ ln(r)□ /□}$□ 1%

(17)
$z_{desired}$□ r□ □ □ □ rcos(□)□ jrsin(□)

Thecontroldutyratioisgivenfrom(10)andcanbemodifiedasfollows;

d(k)□ d(k□1)□$K_1T_sI_{L,ref}$□K_2i_L(k)□□K_1T_s□K_2□i_L(k□1)
(18)

To verify the theoretical analysis, the proposed digitalstate feedback control scheme has been tested by using theMATLABSimulinksoftware.Thebuckconverter
parameterschosenforthissimulationare:
V_g□ 52[V],V_O
□ 28[V],



L_1□ 110[□ H],
r_{L1}
□ 30[m□],
L_2□ 110[□ H],
r_{L2}
Fig.13Theparallelinterleavedbuckconvertercontrolscheme
□ 30[m□],and
F_{SW}□ 100[kHz],whereC isneglectedin
thissimulation.Fromequation(17),thefeedbackgainis
designedas
K_1T_S□ □ 0.0304,
K_2□ 0.1363 .Fig.14shows

4. The Buck Converter Current Mode ControlforDiscrete TimeDomainDesignExample

thetransientcurrentresponseoftheproposedcontrolsystem.Itisobservedthattheinterleavedcurrentsharing among the converter modules is precisely achieved eventhoughtheparasiticresistanceandtheinductancearedifferent.Also,theproposeddiscretestatefeedbackcontrol scheme can meet the required dynamics for thegivenspecifications.

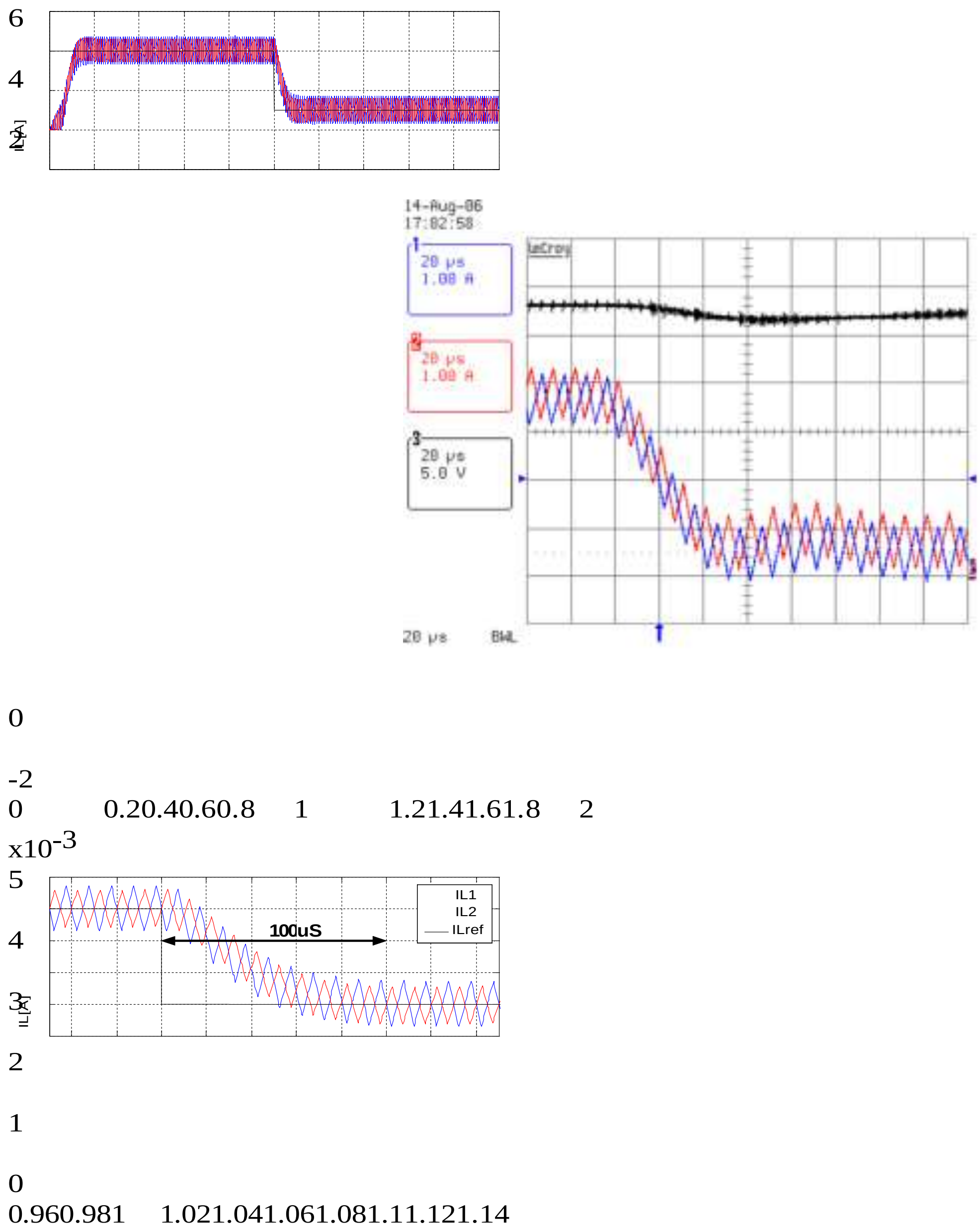
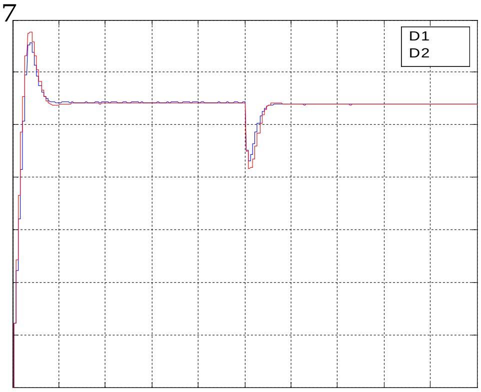


Fig. 15The inductor current response of the proposed statefeedbackcurrentmode control

Theprototypehardware,whichconsistsoftwo100Wparallelmodulebuckconverters,isbuiltasshowninFig.

Time[sec]
x10^{-3}
13.Theconverterparametersare:
V_g 52[V],
V_o 28[V],

0.7



L_1 L_2 100[H],
C 100[F],and
F_{SW} 100[kHz]The

0.6

0.5

0.4
Dutyratio

0.3

0.2

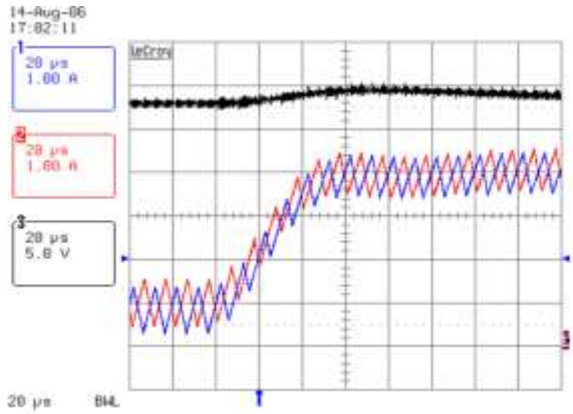
0.1

0
0
0.20.40.60.8 1 1.21.41.6
Time[sec]

1.8 2
x 10^{-3}

DSPimplementationisthesameasthebi-directionalconverter application as described in Section 4. Fig. 15shows the inductor current of each module at the currentcontrolloop,whichisdesignedandsimulatedinthisSection. In this implementation, the output voltage is set to28[V] using a constant voltage mode using electric loadequipment.Theresponsetimeandperformanceofthediscrete state feedback controller are in good agreementwiththesimulationresultsandthustheteoreticalanalysisis confirmed.

Fig. 14The simulation results of the proposed discrete statefeedbackcurrentcontrol



CONCLUSIONS

A digital state feedback control approach using the poleplacementtechniqueisproposedinthecontinuousanddiscrete time domain. Since the analysis and design areperformedinthetimedomainusingthestateequations,thecontrollercanbesystematicallydesignedfortherequired system specifications. For the design example inthecontinuoustimedomainapproach,aprototype42V/14V bi-directional automobile system that consists oftwo synchronous buck/boost converter modules has beenbuilt and tested by using the digital state feedback currentcontrol,whichcansolvetheproblemsoftheanalogcontrolscheme.Forthedesignexampleinthediscrete time domain approach, a parallel module buck converterwas built and tested by using the discrete state feedbackcurrent control. The proposed control system can achieveinterleavedcurrentsharingandcantrackthereferencevalue.

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