Journal of Vibration Engineering

Registered

☑ **SCOPUS**

☑ **GOOGLE SCHOLAR**

☑ **DIGITAL OBJECT IDENTIFIER (DOI)**

☑ **IMPACT FACTOR 6.1**

Our Website
www.jove.science

Single-PhasetoThree-PhaseDriveSystemUsingTwoParallelSingle-PhaseRectifiers

G.MahaboobSubahan[1]

Assistantprofessor

M.Swetha[2]

Assistantprofessor

Electrical and Electronics Engineering Department, Annamacharya Institute of Technology & sciences(Autonomous),Rajampet,Andra Pradesh,India

Abstract—**This paper proposes a single-phase to three-phase drive system composed of two parallel single-phase rectifiers, a three-phaseinverter,andaninductionmotor.Theproposedtopol-ogy permitsto reducethe rectifier switchcurrents, the harmonic distortionat the input converter side, and presents improvements on the fault tolerance characteristics. Even with the increase in the number ofswitches, the total energy loss of the proposed system may be lower than that of a conventional one. The model of the system is derived,and it is shown that the reduction of circulating current is an important objective in the system design. A suitable control strategy,includingthepulsewidthmodulation technique(PWM),isdeveloped.Experimentalresultsarepresentedaswell.**

IndexTerms—**Ac-dc-acpowerconverter,drivesystem,parallelconverter.**

I.INTRODUCTION

Severalsolutionshavebeen proposed whentheobjec-tiveistosupplyathree-phasemotorsfromasingle-phase

ac mains. It is quite common to have only a single- phase power grid in residential, commercial, manufacturing, and mainly inruralareas,whiletheadjustablespeeddrivesmayrequestathree-phasepowergrid.

Single-phase to three-phase ac–dc–ac conversion usually employs a full-bridge topology, which implies in ten power switches,asshowninFig.1.Thisconverterisdenotedhereasconventional topology.

Parallel converters have been used to improve the power capa- bility, reliability, efficiency, and redundancy. Parallel convertertechniques can be employed to improve the performance of active power filters , uninterruptible power supplies (UPS) , faulttolerance of doubly fed induction gener- ators , and three-phase drives , Usually the opera- tion of converters in parallel requires atransformerforisolation.However, weight, size, and cost associated with the transformer maymakesuchasolutionundesirable[20]. When an isolation transformer is not used, the reduction of circulating currents among different converter stages is animportantobjectiveinthesystemdesign.

In this paper, a single-phase to three-phase drive system com- posedoftwo parallel single-phaserectifiers andathree-phaseInverterisproposed,asshowninFig.2.Theproposedsystemisconceivedtooperatewherethesingle-phaseutilitygridistheuniqueoptionavailable.Comparedtotheconventionaltopol-ogy,theproposedsystempermits:toreducetherectifierswitchcurrents;thetotalharmonicdistortion(THD)ofthegridcur-rentwithsameswitchingfrequencyortheswitchingfrequencywithsameTHDofthegridcurrent;andtoincreasethefaulttolerancecharacteristics.Inaddition,thelossesoftheproposedsystemmaybelowerthanthatoftheconventionalcounterpart.Theaforementionedbenefitsjustifytheinitialinvestmentoftheproposedsystem,duetotheincreaseofnumberofswitches.
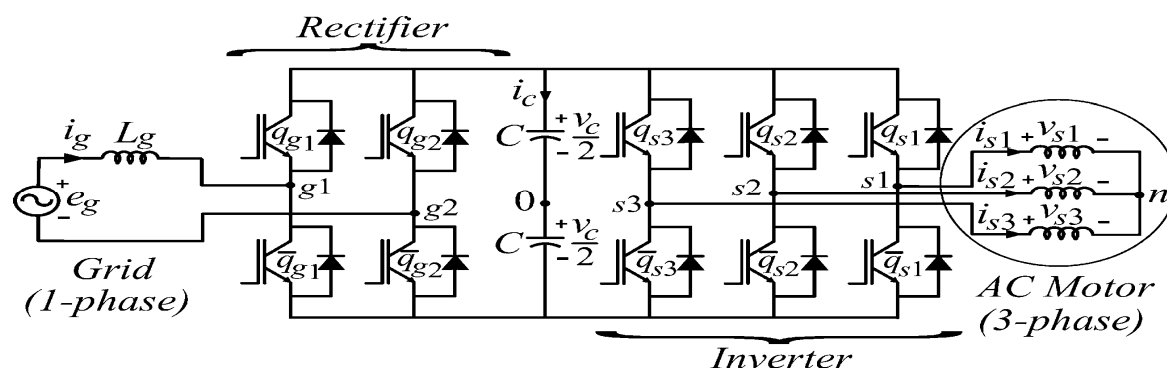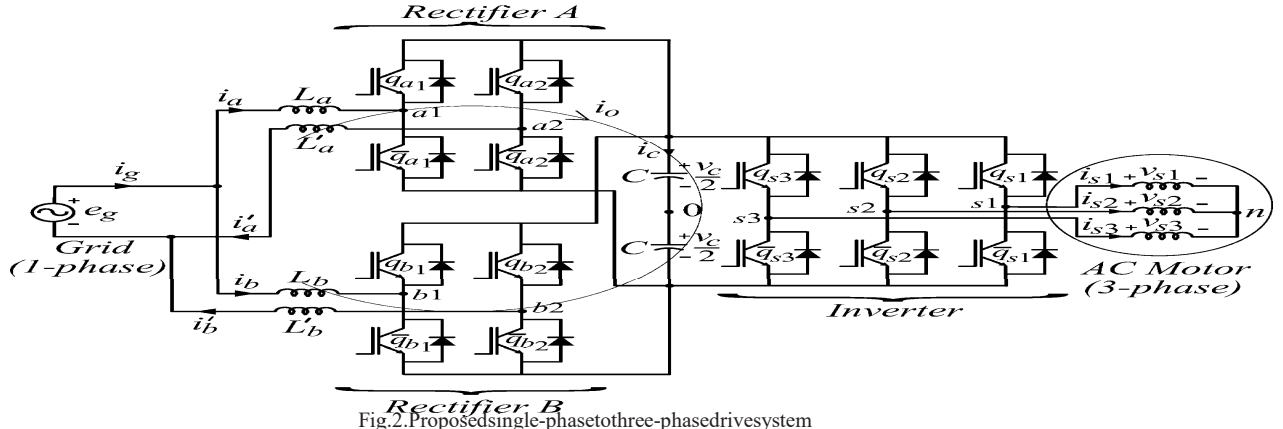
Fig.1.Conventionalsingle-phasetothree-phasedrivesystem

Fig.2.Proposedsingle-phasetothree-phasedrivesystem

II   PWMSTRATEGY

Theinvertercanbecommandedbyusinganadequatepulsewidthmodulation(PWM)strategyforthree-phasevolt-age sourceinverter (VSI)[19], sothat itwillnotbediscussedhere.Inthissection,thePWMstrategy fortherectifier willbepresented.

Theparameterμchangestheplaceofthevoltagepulsesrelatedto$v_a$andv_b.When$v_x^*=v_{x\min}^*(\mu=0)$or$v_x^*=v_{x\max}^*$ ($\mu=1$)areselected,thepulsesareplacedinthebeginorinthe   endofthehalfperiod(T_s)ofthetriangular carriersignal[seeFig.5(a)and(c)].Ontheotherhand,when$v_x^*=v_{x\mathrm{ave}}^*$thepulsesarecenteredinthehalfperiodofthecarriersignal[seeFig.5(b) and(d)].Thechangeofthepositionofthevoltagepulsesleadsalsotothechangein thedistribution ofthezeroinstantaneous voltages (i.e., $v_a = 0$ and $v_b = 0$). With $\mu = 0$ or $\mu = 1$ the zero instantaneous voltages are placed at the beginning or at the endof theswitchingperiod,respectively,while with$\mu=0.5$,theyaredistributedequallyatthebeginningandattheendofthehalfperiod.Thisissimilartothe   distributionofthe   zero- voltagevectorinthethree-phase inverter.

III. CONTROLSTRATEGY

Fig.3presentsthecontrolblockdiagramofthesysteminFig.2,highlightingthecontroloftherectifier. The Rectifier circuit of the proposed system has the same objectives of that in Fig. 1, i.e., to control the dc-link voltage and toguarantee the grid power factor close to one. Additionally, the circulatingcurrent i_o in the rectifier of the proposed system needs tobecontrolled.

Inthisway,thedc- linkvoltage$v_c$isadjustedtoitsreferencevaluev_c^*usingthecontrollerR_c,whichisastandardPItypecontroller.Thiscontrollerprovidestheamplit udeoftherefer-encegridcurrentI_g^*.Tocontrolpowerfactorandharmonicsin thegridside,theinstantaneousreferencecurrenti_g^*mustbesynchronizedwithvoltagee_g,asgiveninthevoltage-oriented

(VOC)forthree-phasesystem[32].Thisisobtainedviablocks$Ge-ig$,basedonaPLLscheme.Thereferencecurrentsi_a^* andi_b^* areobtainedbymaking$i_a^*=i_b^*=i_g^*/2$,whichmeansthateachrectifierreceiveshalfofthegridcurrent.Thecontrol of the rectifier currents is implemented using the controllers indicated by blocks $R_a$and R_b. These controllers can be imple- mentedusinglinearornonlineartechniques[33]–[37].Inthispaper,thecurrentcontrollawisthesameasthatusedinthetwo sequences synchronous controller described in [38]. These current controllers define the input reference voltages $v_a^*$and v_b^*.

Thehomopolarcurrentismeasured(i_o)andcomparedtoitsreference($i_o^*=0$).TheerroristheinputofPIcontroller$R$,that determinesthevoltagev_o^*.Thecalculationofvoltagev_x^*isgivenfrom(30)to(32)asafunctionofμ,selectedasshownninthe SectionV.Themotorthere-phasevoltagesaresuppliedfromtheinverter(VSI).BlockVSI-Ctrindicatestheinverteranditscontrol. The control system is composed of the PWM command and a torque/flux control strategy (e.g., field-orientedcontrol orvolts/hertzcontrol).
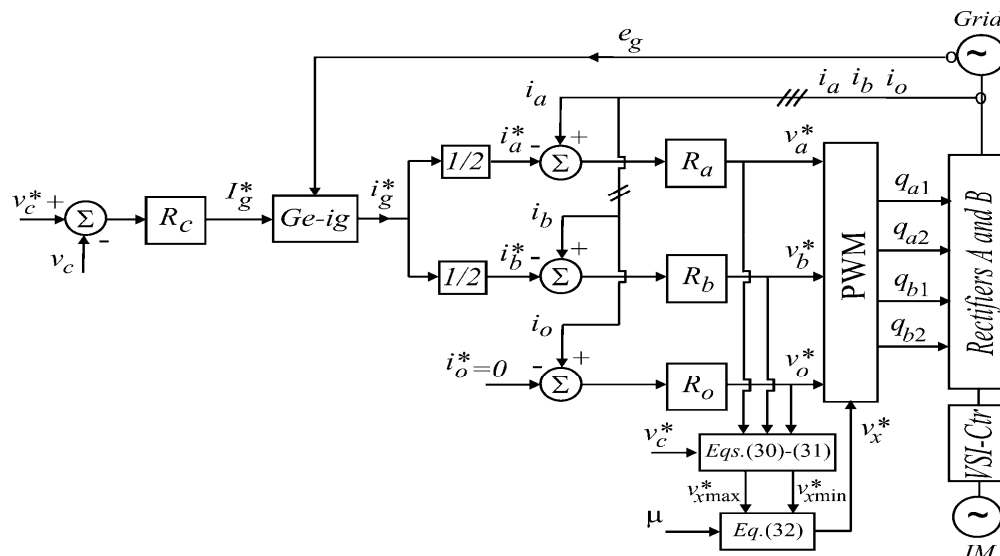
Fig.3.Controlblockdiagram.

IV. HARMONICDISTORTION

The harmonic distortion of the converter voltages has been evaluated by using the weighted *THD* (*WTHD*).Fig. 4 shows theWTHDof voltagesgenerated byrectifiers [v_{ab}=(v_a+v_b)/2fortheproposedconfigurationandv_g=v_{g10}

v_{g20}fortheconventional

one]atratedgridvoltageasafunctionofμ.Notethattheparameterμdetermines$v_x^*$from.Theresultantvoltagev_{ab} generatedbyrectifier isresponsibletocontroli_g[see(16)],whichmeansthatthisvoltageisusedtoregulatetheharmonicdistortionoftheutilitygrid.
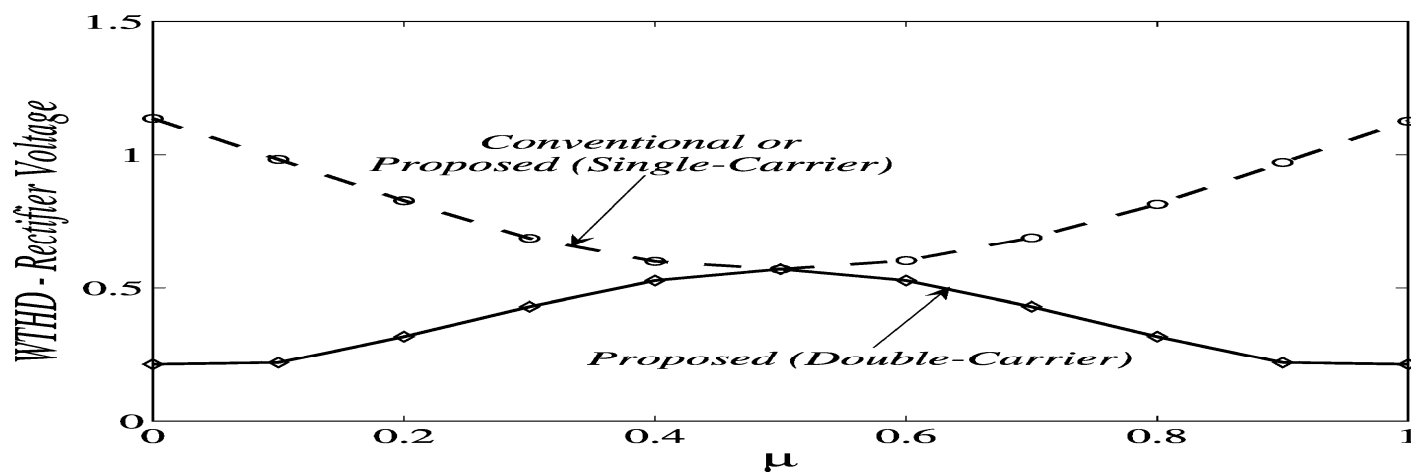

Fig.4.*WTHD*of rectifiervoltage(v_{ab}forproposedconfiguration and $v_g$forstandardconfiguration)asafunctionofμ.

When the single-carrier PWM is used, the behavior of *WTHD* of the proposed system is similar to that of conventional one forallμ,asobservedinFig.4.Whenthedouble-carrierPWM is used with μ = 0.5, the *WTHD* is also the same for both configurations.However, for the other values of μ the *WTHD* ofthe proposed system is lower than that of the conventional one. The *WTHD* of theproposed topology (double-carrier with μ = 0 or μ = 1) is close to 63% of that of the conventional topology (with μ = 0.5). Thestudy has also shown that it is possible to reduce the switching frequency of the proposed system in 60% and still have the same*WTHD*ofthestandardconfiguration.

The*WTHD*behaviorinFig.4canbe explainedfromFig. 5.Thatfiguredepictsthepolevoltages(v_{a10},v_{a20},v_{b10},v_{b20})andtheirreferences ($v_a{}^*10$, $v_a{}^*20$, $v_b{}^*10$, $v_b{}^*20$), the triangular carriersignals (v_{t1} , v_{t2}), the resultant rectifier voltage (v_{ab}) and thecirculating voltage (v_o). Fig. 5(a) and (c) shows these variableswith single-carrier (with μ = 1) and double-carrier (with μ =1),respectively. For the double-carrier [see Fig. 5(c)] the voltage v_{ab}has smaller amplitude and better distribution along the halfswitching period than that of single-carrier [see Fig. 5(a)], which means a lower *WTHD* (as observed in Fig. 4 for μ = 1). On theotherhand,forμ=0.5[seeFig.5(b)and(d)]thedistributionofvoltagev_{ab}alongtheswitchingperiodisthesameforbothcases,i.e.,single-carrierand double-carrierhave the same *WTHD*(asobservedinFig.4forμ=0.5).

Besides the total harmonic distortion (*THD*) of the grid cur-rent i_g , associated to the *WTHD* of the voltage v_{ab} , the har-monicdistortion analysis must also consider the currents in therectifiers. This is an important issue due to losses of the con-verter [39],[40].Theharmonicdistortionoftherectifiercurrents(i_a,i_a^J,i_b,andi_b^J)withdouble-carrierishigherthanthatofthegridcurrent i_g . When the parallel rectifier with double-carrier is used, the *THD* of all these currents are reduced for μ = 0 or μ = 1 andincreasedforμ=0.5.Ontheotherhand,the*THD*ofthecirculatingcurrentisalsosmallerwithμ=0orμ=1.Fig.6shows currentsi_a,$i^J{}_a$,and$i_o$fordouble-carrierwithμ=1andμ=0.5.Itcanbeseenthatthemeanvaluesoftheripplesofallcurrentsaresmallerwhenμ=1isselected.Inconclusion,
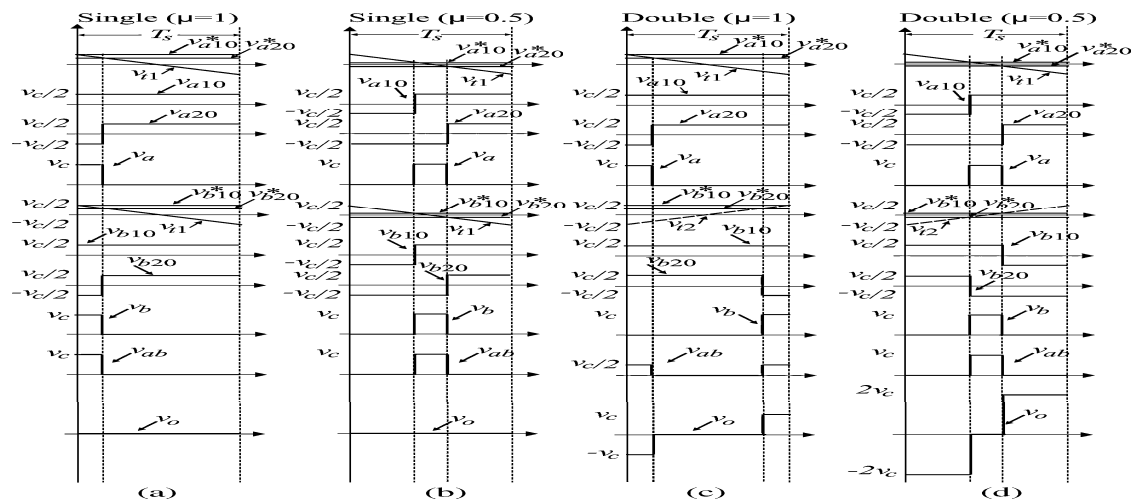

Fig. 5. Variables of rectifiers A and B. (a) Single-carrier with μ = 1. (b) Single-carrier with μ = 0.5. (c) Double-carrier with μ = 1. (d) Double-carrierwithμ=0.5.

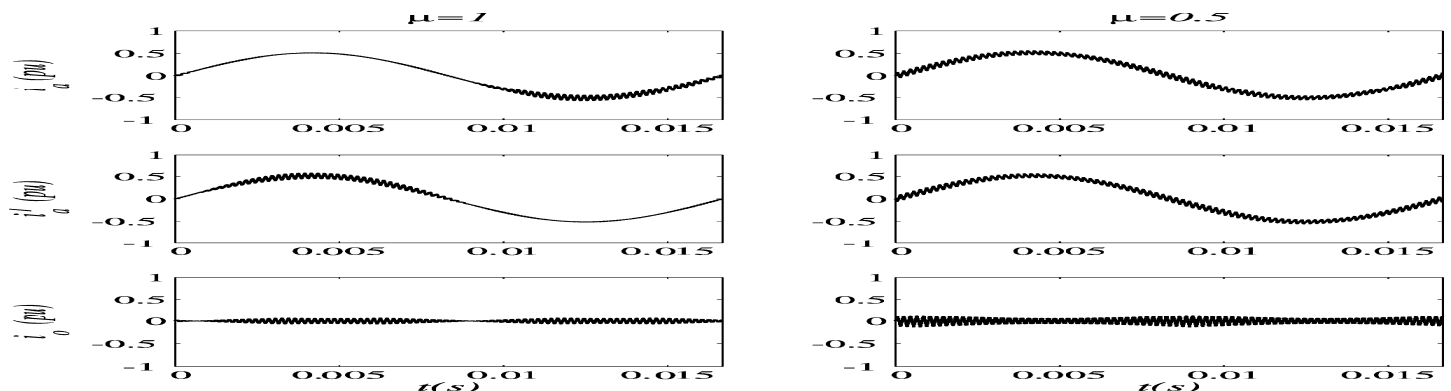Fig.6.Currentsi_a,i_a^J,and$i_o$fordouble-carrierwithμ=1andμ=0.5.

the optimal rectifier operation is obtained with double-carrier making $\mu = 0$ or $\mu = 1$. A four-carrier approach may alsobe used. Compared with the two-carrier strategy, the four-carrier strategy permits to reduce the harmonic distortion ofthegridcurrent,butincreasestherectifierlosses.
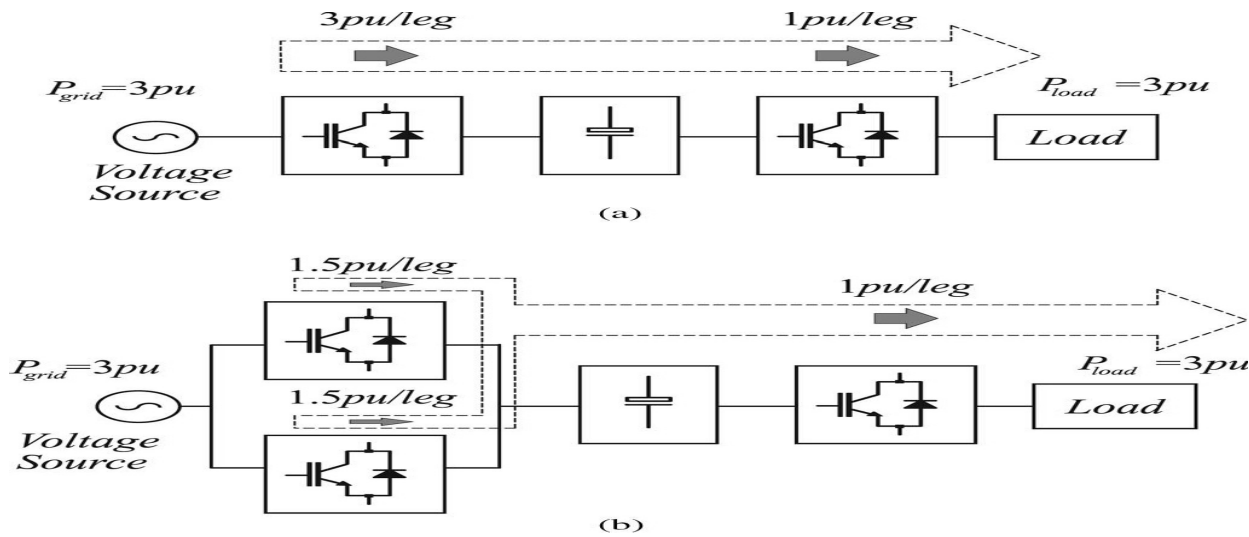

Fig. 7.Flow of active power. (a) Conventional ac–dc–ac single-phase to three- phase converter. (b) Proposed system with tworectifiers.

V.RATINGSOFSWITCHES

Assuming same rms voltages at both grid and machine sides, a machine power factor of 0.85 and neglecting the converterlosses,currentsoftherectifierswitchesnormalized interms of currents of the inverter switches are 2.55 and 1.27 for theconventional and the proposed single-phase to three-phase con- verter, respectively. Fig. 7(a) and (b) shows the flow of activepowerintheconventionalandintheproposedsingle-phaseto

three-phase converter, respectively. For balanced system ($L^{\jmath}g = L_a = L^{\jmath}a = L_b = L_b{}^{\mathrm{J}}$), voltage v_o is close to zero, so thatthedc-linkvoltageisequaltothatrequiredbytheconventionalsys- tem.Sincetheparallelconnectionschemepermitstoreducetheswitchcurrents andpreserve thedc- linkvoltage,theratingofeachpowerswitchintherectifiersideisreduced.

VI. DC-LINKCAPACITOR

The dc-link capacitor current behavior is examined in this section. Fig. 8 illustrates the harmonic spectrums of the dc- linkcapacitorcurrentfortheconventionalconverter(μ=0.5)[seeFig.8(a)]andfortheproposedconverterusingsingle-carrierwithμ = 0.5 [see Fig. 8(b)], double-carrier with μ = 0.5 [see Fig. 8(c)] and double-carrier with μ = 0 [see Fig. 8(d)]. The proposedconverter using double-carrier with μ = 0 provides the best reduction of the high frequency harmonics. Table I (obtained fromFig.8)presentsthe*THD*ofthedc- linkcapacitorcurrentoftheproposedconverter(*THDp*)referredtothe*THD*oftheconventionalconverter (*THDc*). The highest reduction of *THD* is obtained for the converter using double-carrier with μ=0. The *THD*obtainedforμ=1isequaltothat forμ=0.
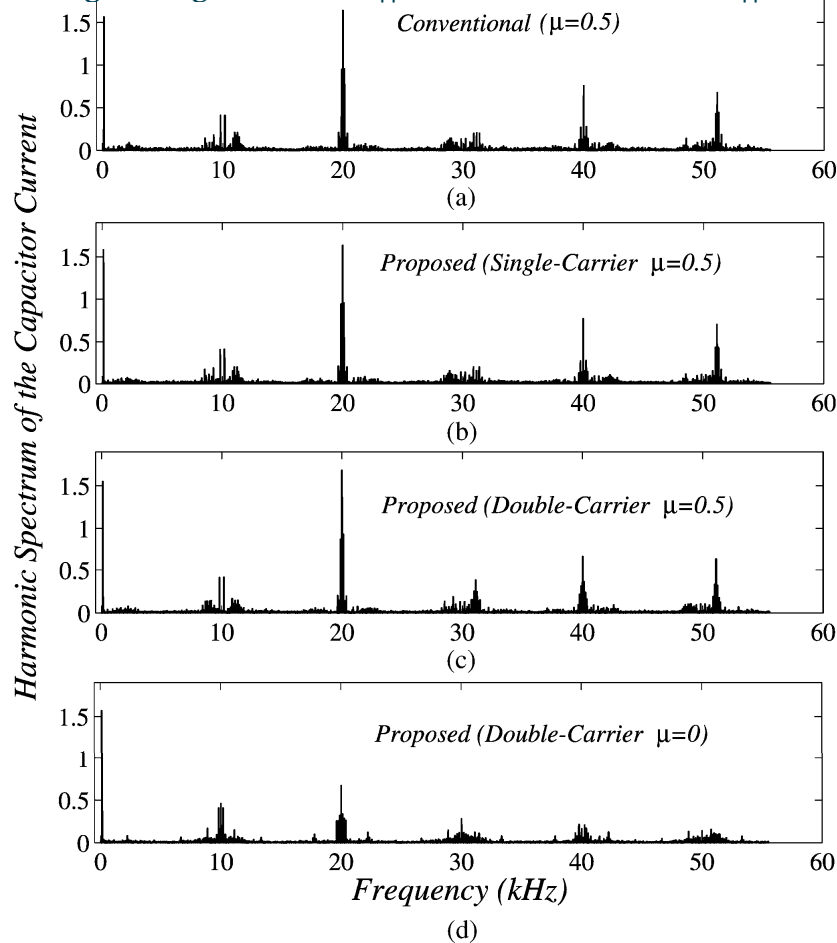
Fig.8.Harmonicspectrumofthedc-linkcapacitorcurrent.(a)Conven-tionalconverter

TABLEI
NORMALIZEDTHDOFDC-LINKCURRENTOFTHEPROPOSEDCONVERTER

Topology (PWM)	$THDp/THDc$
Proposed (Single $\mu = 0.5$)	0.994
Proposed (Double $\mu = 0.5$)	1.002
Proposed (Double $\mu = 0$)	0.717

Itispossibletoreducethesecondorderharmonicintro-ducedbysingle-phase operation,butthisis not ofinterestbe-causeitrequiresunbalancingandincreasingrectifiercurrents$i_a$and i_b.

VII. LOSSESANDEFFICIENCY

The evaluation of the rectifier losses is obtained through re-gression model .The switch loss model in- cludes: 1) IGBT anddiode conduction losses; 2) IGBT turn-ON losses; 3) IGBT turn-OFF losses; and 4) diode turn-OFF energy.The loss evaluationtakesintoaccountjusttherectifiercircuit, since the inverter side of converter is the same for the proposed and standardconfigurations.

When the rectifiers operate with a switching frequency equalto 5 kHz, the conduction and switching losses of the proposedtopologywere70%and105%,respectively,ofthecorrespond-inglossesofthe conventionaltopology.Consequently,inthiscase,the total losses of the proposed topology was smaller than that of the conventional topology. The increase of the switch- ingfrequency does not change the conduction losses of both topologies, but increases their switching losses, especially for theproposedtopologythathasahighnumberofswitches.

Theefficiencyofthetopologiesoperating withaswitch- ing frequency equal to 10 kHz and 5 kHz was evaluated byexperimental measurement with a 2 kW load. Table II shows the experimental results of the rectifier efficiency. Such resultsareobtainedfortheproposedsystem(η_p) normalized in terms conventional one (η_c), for three cases: 1) both rectifiers op- erating at 10kHzandL^j_g= L_g;2)bothrectifiersoperatingat 10 kHzandL^j_g= L_g /2;and3)bothrectifiers operatingat5 kHz and L^j_g=L_g .Three strategies areconsideredintermsofPWMcontrol:1)single-carrierwithμ=0.5(S-Caμ=0.5);

VIII.EXPERIMENTALRESULTS

The system shown in Fig. 2 has been implemented in the laboratory. The setup used in the experimental tests is based onamicrocomputer equipped with appropriate plug-in boards andsensors. The system operates with a switching frequency equalto10kHz.Steadystate,transient,faultanalysis,andinterleaveoperationhavebeenevaluatedintheexperimentaltestes.

The steady-state experimental results are shown in Fig. 12. The waveforms in this figure are: (a) voltage and current ofthegrid, (b) dc-link voltage, (c) currents of rectifier A and circulating current, (d) currents of rectifiers A and B, and (e) load linevoltage. Note that, with the proposed configuration, all control demanded for single-phase to three-phase converterhas beenestablished. The control guarantees sinusoidal grid currentwithpowerfactorclosetoone[seeFig.12(a)],dc- link andmachine voltages under control [see Fig. 12(b) and (e)]. Furthermore, the proposed configuration provides currentreduction intherectifierside(halfofthecurrentofthestandardtopology)[seeFig.12(d)],whichcanprovide   loss   reduction. Also,thecontrolguaranteesthecirculatingcurrentclosetozero[seeFig. 12(c)].
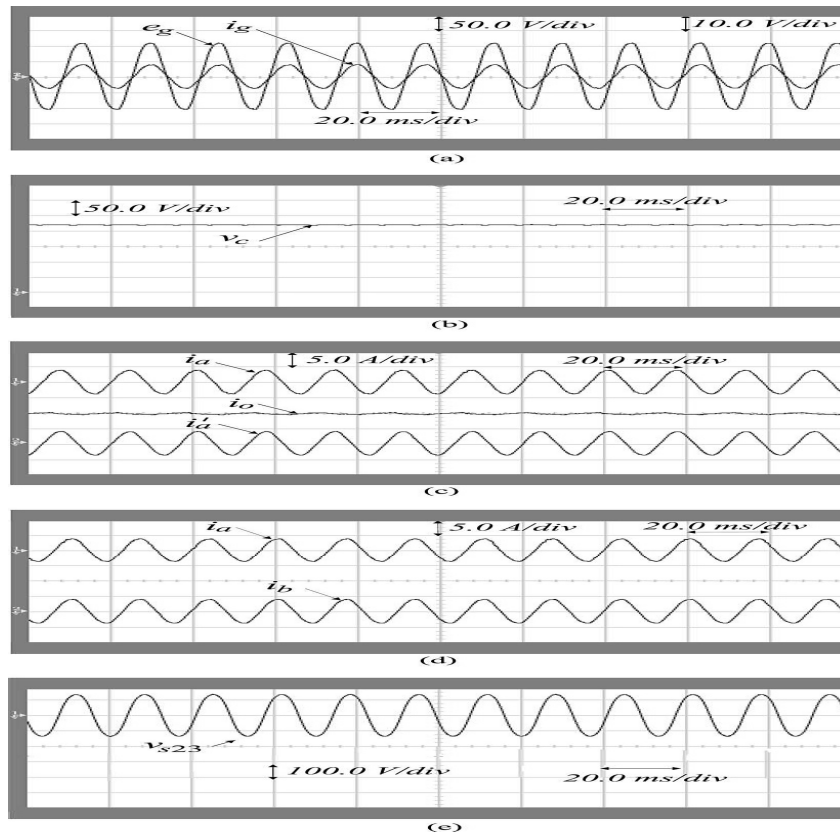

Fig. 12. Steady-state experimental results. (a) Grid voltage (e_g) and gird current (i_g). (b) Capacitor voltage (v_c). (c) Currents ofrectifier A($i_a$andi^j_a)andcirculating current (i_o).(d)CurrentsofrectifiersA(i_a)andB(i_b).(e)Linevoltageoftheload(v_{s23}).
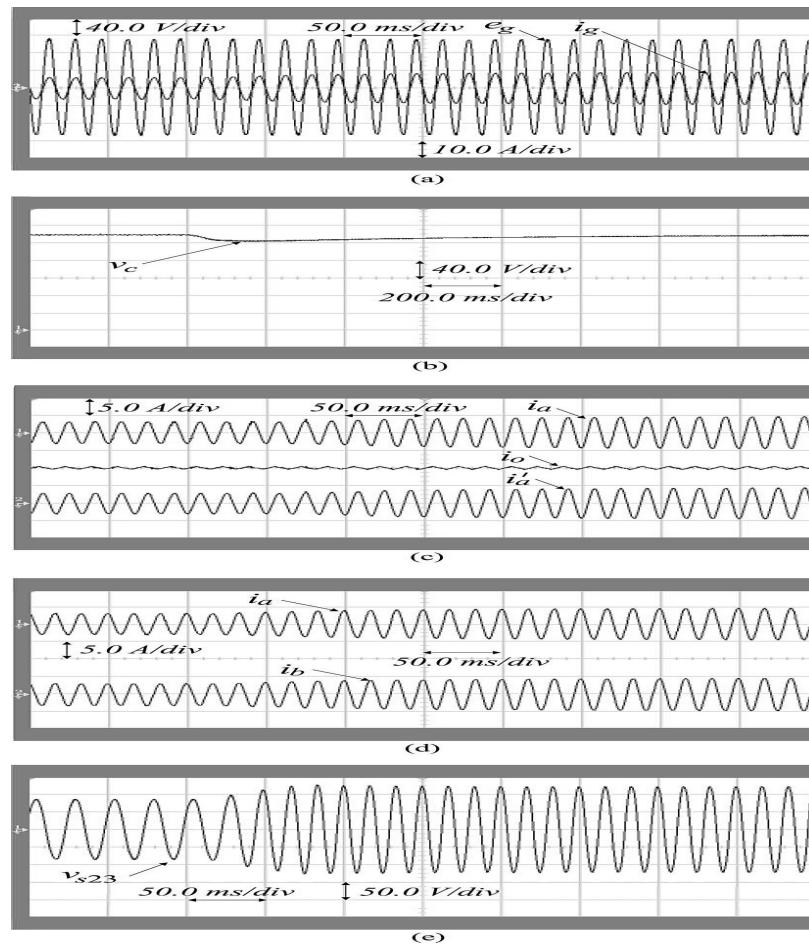
Fig.13.Experimentalresultsforavolts/hertztransientappliedtothethree-phasemotor.(a)Gridvoltage(e_g)andgirdcurrent(i_g).(b)Capacitorvolt-age(v_c).(c)CurrentsofrectifierA($i_a$andi^j_a)andcirculatingcurrent(i_o).
(b) Currents ofrectifiersA(i_a)andB(i_b).(e)Linevoltageoftheload(v_{s23}).

IX.Conclusion

A single-phase to three-phase drive system composed of twoparallel single-phase rectifiers, a three-phase inverter and an induction motor was proposed. The system combines two parallelrectifiers without the use of transformers. The system model and thecontrolstrategy,includingthePWMtechnique,have beendeveloped.

The complete comparison between the proposed and standard configurationshas been carried out in this paper.Compared to theconventional topology, the proposed system permits to reduce the rectifier switch currents, the *THD* of the grid currentwith sameswitchingfrequencyortheswitchingfrequencywithsame*THD*ofthegridcurrentandtoincreasethefaulttolerancecharacteristics.In addition,the losses oftheproposedsystem maybelowerthanthatoftheconventionalcounterpart.

The initial investment of the proposed system (due to high number of semiconductor devices) cannot be considered a drawback,especiallyconsideringthescenariowherethecitedadvan-tagesjustifysuchinitialinvestment.

Theexperimentalresultshaveshownthat thesystemiscon-trolledproperly,evenwithtransientandoccurrenceoffaults.

REFERENCES

[1] P.EnjetiandA.Rahman,"AnewsinglephasetothreephaseconverterwithactiveinputcurrentshapingforlowcostACmotor drives," *IEEE Trans.Ind.Appl.*,vol.29,no.2,pp.806–813,Jul./Aug.1993.

[2] J.ItohandK.Fujita,"Novelunitypowerfactorcircuitsusingzero-vectorcontrolforsingle-phaseinputsystems,"*IEEETrans.Power Electron.*, vol.15, no.1,pp.36–43,Jan.2000.

[3] B. K. Lee, B. Fahimi, and M. Ehsani, "Overview of reduced parts converter topologies for AC motordrives," in *Proc.IEEEPESC*,2001,pp.2019–2024.

[4] C.B.Jacobina,M.B.deR.Correa,A.M.N.Lima,andE.R.C.daSilva,"ACmotordrivesystemswithareducedswitchcountconverter,"*IEEE Trans.Ind.Appl.*,vol.39,no.5,pp.1333–1342,Sep./Oct.2003.

[5] R.Q. Machado,S. Buso,andJ. A. Pomilio,"A line-interactivesingle-phase tothree-phaseconvertersystem,"*IEEETrans.PowerElectron.*, vol.21,no.6,pp.1628–1636,May 2006.

[6] O.Ojo,W.Zhiqiao,G. Dong,andS.Asuri,"High-performancespeed-sensorless control ofan inductionmotordriveusinga minimalistsingle-phase PWMconverter,"*IEEE Trans.Ind.Appl.*,vol.41, no.4,pp.996–1004,Jul./Aug.2005.

[7] J.R.Rodr´ıguez,J.W. Dixon, J. R. Espinoza,J.Pontt,andP. Lezana,"PWMregenerativerectifiers:Stateoftheart,"*IEEETrans.Ind.Electron.*,vol.52,no. 1,pp.5–22,Feb.2005.

[8] M.N.Uddin,T.S.Radwan,andM.A.Rahman,"Fuzzy-logic-controller-basedcost-effectivefour-switchthree-phaseinverter-fedIPMsynchronousmotordrivesystem,"*IEEETrans.Ind.Appl.*,vol.42,no.1,pp.21–30,Jan./Feb.2006.

[9] D.-C.LeeandY.-S.Kim,"Controlofsingle-phase-to-three-phaseAC/DC/ACPWMconvertersforinductionmotordrives,"*IEEE Trans.Ind.Electron.*, vol.54,no.2,pp.797–804,Apr.2007.

[10] L. Woo-Cheol, L. Taeck-Kie, and H. Dong-Seok, "A three-phase parallel activepowerfilter operatingwithPCCvoltagecompensationwithconsid-erationforanunbalancedload,"*IEEETrans.PowerElectron.*,vol.17,no.5,pp.807–814,Sep.2002.

[11] L. Asiminoaei, C. Lascu, F. Blaabjerg, and I. Boldea, "Performance im- provement of shunt active power filter with dualparalleltopology,"*IEEETrans.PowerElectron.*,vol.22,no.1,pp.247–259,Jan.2007.

[12] L. Asiminoaei, E. Aeloiza, P. N. Enjeti, F. Blaabjerg, and G. Danfoss, "Shunt active-power-filter topology based onparallelinterleavedinvert-ers," *IEEE Trans.Ind.Electron.*,vol.55,no.3,pp.1175–1189,Mar.2008.

[13] T.A.Chaer,J.-P.Gaubert,L.Rambault,andM.Najjar,"Linearfeedbackcontrolofaparallelactiveharmonicconditionerinpowersystems,"*IEEETrans.PowerElectron.*,vol.24,no.3,pp.641–653,Mar.2009.

[14] M. Ashari, W. L. Keerthipala, and C. V. Nayar, "A single phase parallely connected uninterruptible power supply/demandside management sys-tem," *IEEETrans.EnergyConvers.*,vol.15,no.1,pp.97–102,Mar.2000.

[15] M. Pascual, G. Garcera, E. Figueres, and F. Gonzalez-Espin, "Robust model-following control of parallel UPS single-phaseinverters,"*IEEE Trans.Ind.Electron.*,vol.55,no.8,pp.2870–2883,Aug.2008.

[16] J.Guerrero, J.Vasquez,J.Matas,M.Castilla,and L.deVicuna,"Con-trolstrategyforflexiblemicrogridbasedonparallelline-interactiveUPSsystems,"*IEEETrans.Ind.Electron.*,vol.56,no.3,pp.726–736,Mar.2009.

[17] P.FlanneryandG.Venkataramanan,"Afaulttolerantdoublyfedinductiongeneratorwindturbineusingaparallelgridsiderectifier andseriesgridsideconverter," *IEEE Trans.PowerElectron.*,vol.23,no.3,pp.1126–1135,May 2008.

[18] R. M. Cuzner, D. J. Nowak, A. Bendre, G. Oriti, and A. L. Julian, "Miti- gating circulating common-mode currentsbetweenparallelsoft-switcheddrivesystems,"*IEEETrans.Ind.Appl.*,vol.43, no. 5,pp.1284–1294, Sep./Oct. 2007.

[19] C.B.Jacobina,E.C.dosSantosJr.,E.R.C.daSilva,M. B.R.Correa, A. M. N. Lima, and T. M. Oliveira, "Reduced switch count multiple three- phase ac machine drive systems," *IEEE Trans.PowerElectron.*,vol.23,no.2,pp. 966–976, Mar. 2008.

[20] J.-K. Park, J.-M. Kwon, E.-H. Kim, and B.-H. Kwon, "High-performance transformerless online UPS," *IEEE Trans. Ind.Electron.*,vol.55,no.8,pp.2943–2953,Aug.2008.