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SimulationStudyoftheThree-PhaseFlyingCapacitorInverters:Modulation Strategies and Applications

Sanjeevani Gondane
Student of MTech
TulsiramjiGaikwad Patil College of Engineering and Technology
Mohagaon, Wardha Road, Nagpur, Maharashtra
Email: sanjeevanigondane@gmail.com

Pratik Ghutke
AP, Electrical Engineering Department
TulsiramjiGaikwad Patil College of Engineering and Technology
Mohagaon, Wardha Road, Nagpur, Maharashtra
Email: pratik.electrical@tgpcet.com

ABSTRACT

Thispaperisasimulation studyofmodulationstrategiesinthree-phaseflyingcapacitorinvertersinMATLABsimulink.Theflying capacitormultilevelconverterisarecentlydevelopedconverte rtopologyassuringaflexiblecontrolandmodulardesign.Howe ver,theflyingcapacitormultilevelconverterrequiresabalanced DCvoltagedistribution. This canberealizedbyusingaspecialcontrolleadingtonaturalbalanc ingorbymeasuringthevoltagesandselectingtheappropriateswi tchingstate..Underinvestigationthosestrategiesthatsolvetheca pacitorvoltagebalancingproblem,Carrierbasedphase-shiftPWMmethodwithAPOD,IPD,PODarepresentedandcorr espondingvoltageharmonicdistortionvaluesareanalyzed3lev elfivelevelFlyingcapacitormultilevelinverters.Ageneralmath ematicalmodelforanN-levelinverterisusedforcircuitoperationanalysisandAreviewp owersystemapplicationsofflyingcapacitormultilevelinverters arepresented.

Keywords:FlyingCapacitormultilevelconverters(FCMLC), MATLABsimulinkmodel,Phase-shiftPWMmethod.

1. INTRODUCTION

Increasingdemandforindustrialpowerconvertersandsome of interestingadvantagesofmultilevelinverterssuchaslowdistort ioninoutputvoltagewithrelativelowswitchingfrequency,lowh armonicandelectromagneticinterference(EMI),attractedresea rcherattentions.Uptonow,severaltopologiesofmultilevelinver terarepresented.Themainapplicabletopologiesare DiodeClam pedInverter(DCI),FlyingCapacitorInverter(FCI)andCascade dMultilevelInverter(CMI).Inordertoachievethishigherpower rating,thevoltageandcurrentcapabilitiesofthedevicesusedinth econverterneedtobeincreased.Currentinsulatedgatebipolartra nsistor(IGBT)technologyex-tendsupto6.5kV900Aperswitchingdevice.

MeynardandFochintroducedaflying-capacitor-basedinverterin1992.Theflyingcapacitorinverterhavemanyattr activepropertiesformediumvoltageapplications,includinginpart icularlytheadvantageoftransformerlessoperation,andtheabilityto naturallymaintainthecellcapacitorvoltagesattheirtargetoperatin glevels[1].Thispropertyiscallednaturalbalancing,andallowsinp rinciplethe construction ofsuchinverterswithalargenumberofvol tage levels.Thethree cellimplementation ofthis circuitisshowninFigure1,usesaseriesconnectionof“cells”compr isingaflyingcapacitoranditsassociatedcomplimentaryswitchpai r,andproducesaswitched.

Theproposedmodelforstudyofthecarrier-basedPWMmethodinthree-phaseflyingcapacitorinvertersisbasedoninverterswitchingfunct ionratherthanactualcircuitconfiguration.Thismodelwillbeusedf orharmonicanalysisoftheoutputvoltageoftheinverterfordifferen tPWMstrategies.Theanalyzed PWMstrategiesarethosewhichallowthevoltagebalancingofflyin gcapacitors.SectionIIgivesbasicofFlyingcapacitorfor3levelandfivelevelwithmathematicalmodel,SectionIIIgivesmodulationst rategiesandsimulationmodel SectionIV simulationandanalysis andlastlySectionVpresentedvariouspowersystem applicationsandSectionVIconclusionsaredrawn.

2. FLYINGCAPACITORMULTILEVELI NVERTER

ThepowerswitchesareOperationofFlyingcapacitorMultilevelin vertersoperatedascomplementarypairs(SL1andSL1',etc.),andi ntermediaryvoltagelevelsarerealizedbyroutingtheloadcurrentt hroughpathsthatincludetheclamping-orcell-capacitorsflying-capacitormultilevelinverterusedforsynthesizingapproximatedsi nusoidalloadvoltagesusingstaircaseanglecommutationcontrol. Thebasicoperationisdescribedandamathematicalmodelisusedto investigateallswitchingpermutations.

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A) BasicCircuitOperation

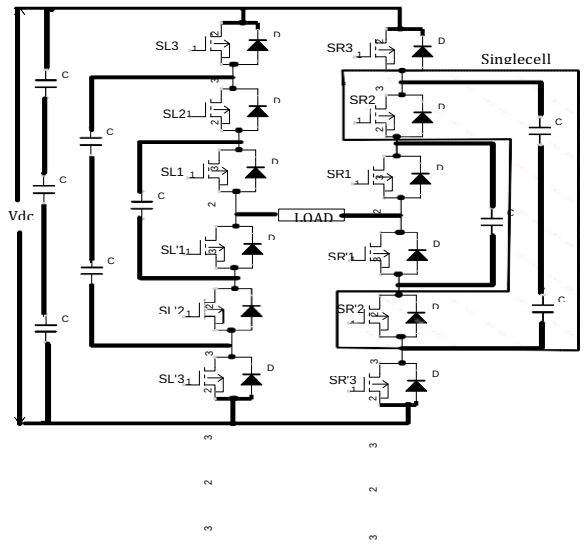

Figure.1.SchematicofFCMLI.(Cellsconnectedinseries)

Theflying-capacitorinvertercanbeconstructedtogiveanunlimitednumberofvoltagelevels,butforpracticaldesignstheyarenormallylimitedtosevenlevelsThenumberofpossiblevoltagelevelsisrelatedtothenumberofpowerswitchingdevicesconnectedinseriesineachinverterleg.Thecircuittopology'sinverterlegisintheformofaseriesofconnectedcellsnestedinwardlytowardtheloadfromthedc-link.Eachcell,shownhighlightedinFigure1,hasacapacitorandtwopowerswitcheseachcomprisingatransistorwithananti-paralleldiodeandoperated ina complementary manner.InanN-cellinverter,eachlimbhas2Nswitchesandappliesn+1distinctdcvoltagelevelsfromzerotoV$_{dc}$acrossttheload.Thesingle-phaseinverterfull-bridgecanalsoapplynegativevoltagelevelsacrosstheloadandsoanN-cellinverterhas2N+1distinctvoltagelevels.Inabalancedinverter,thefloatingcell-capacitoraveragevoltagesarekeptatmultiplesoftheV$_{dc}$/N.Thecapacitorassociatedwiththecomplementaryswitchpairnearesttheloadterminalwillhavethelowestvoltage(V$_{dc}$/N),whilethehighestvoltage((N-1)V$_{dc}$/N)capacitorisassociatedwithswitchesconnectedtoV$_{dc}$. Thevoltagecontributionofeachhalf-limbwilldependonthenumberofswitchesinconductioninitsupperportion.Thereforewithswitchesinconduction,the mthvoltagelevelisappliedattheloadterminalwithrespecttozero.Thefullloadvoltageisthedifferencebetweentheleftandrighthalf-limbvoltagelevels.Thisvoltagecanbeexpressedas

$$V_{load} = \frac{V_{dc}}{N} \times \left(\sum_{n=1}^{N} S_{Ln} - \sum_{n=1}^{N} S_{Rn} \right) \quad \ldots.(1)$$

whereS_{Ln}andS_{Rn}(n=1,2,…N)representtheleftandrighthalf-limbcellswitchstates,respectively,andlogic'1'representstheupperswitchinconductionandthelowerswitchinitsblockingstate.

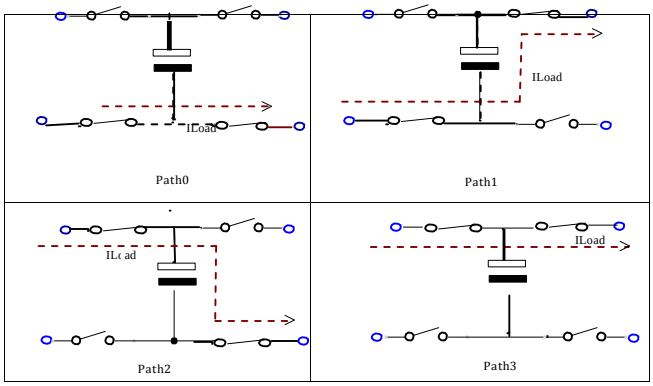

Figure2:Cell-CapacitorCurrentPaths

B) CapacitorVoltageBalancing

Oneofthemainreasonsforusingthemultilevelflying-capacitorinverteristooperateatvoltageshigherthantheindividualpowerswitchblockingcapability.Safeoperationentailskeepingthecell-capacitorvoltagedifferenceswithinrestrictedvoltagebandsandsothecapacitorvoltagesarebalanced.Theflying-capacitorinvertercanoperatewithinherentcapacitorvoltagebalancing,solongasthecontrolutilizesallthemodesofchargingandchargingatanintermediaryvoltagelevel .Figure2showsallthepossiblecurrentpathsforonecell-capacitor.

Thepaths0and 3,andthepaths1and2formcomplementarypairswheretheircorrectusagecanensurecapacitorvoltagebalancingandpowerlosssharing.Inthesteadystate,paths1and2usedoverconsecutivecycleswillbalancethecapacitorvoltageanddevic

elosses,aslongastheoperatingperiodcoincideswitht hesameangularpositioninthecycle.Thiswillleadton onetchangeinthechargeonthecapacitor,sincethecur rentintegralsforeachpathwouldbeequalandofoppos itepolarity.Inthecaseofpaths0and3,theircompleme ntaryusagemustentailangularperiodswherethecurr entisofequalandoppositepolarity,thusensuringthel ossesineachpowerdevicearethesame.

C) CircuitMathematicalModel

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Thefundamentaloperationandcharacteristicsoftheflying-capacitorinverter canoffera greatdeal of flexibilityin termsofoperatingmodescomparedtoconventionaltwo-levelbridges.Complexityincreasesdramaticallyasthenumber oflevelsincreases,andthismakesitdifficulttoanalyzethecircuit' soperation.Therefore,asimplemathematicalmodelisdevelope dwhichcanassistcircuitanalysisunderdifferentswitchstates.T hemathematical equationsfortheinverter are constructed byexpressingthe rateofchangeofcellcapacitorvoltage,theoutputload voltageandcurrentforallvalidswitchingstates.Theequationsar einageneralizedformapplicabletoanyN-cellinverterandthepowerswitchstatesareincludedseparately.T husthematrixformofthemodelforageneralizedinverterhalf-limb(chopper)withanR-Lload,showninFigure3,isasgivenbelow:

$$\frac{d[V]}{dt} = -[C] \times [A]^T \times [S] \times i_0 \qquad \ldots\ldots(2)$$

$$V_{Cn} = \left[[S]^T \times [A]\right] \times [V] \qquad \ldots.(3)$$

$$\frac{di_0}{dt} = \frac{1}{L}(V_0 - Ri_0) \qquad \ldots.(4)$$

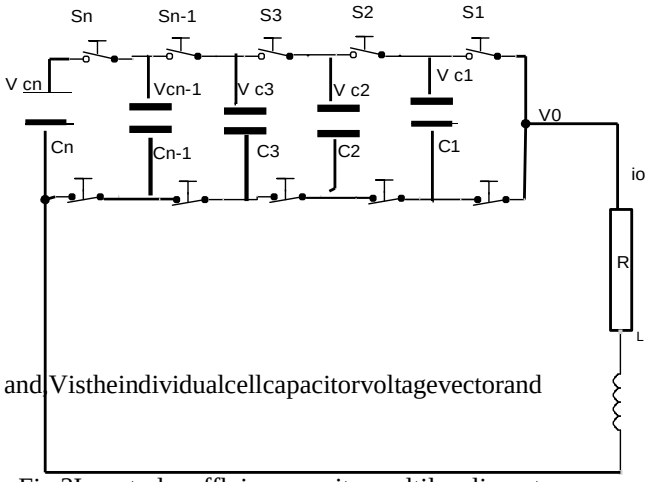
where,

$$V = \begin{bmatrix} v_{C_a} \\ v_{C_{a-1}} \\ \cdots \\ v_{C_2} \\ v_{C_1} \end{bmatrix} \quad S = \begin{bmatrix} S_n \\ S_{n-1} \\ \cdots \\ S_2 \\ S_1 \end{bmatrix}$$

$$A = \begin{bmatrix} 1 & -1 & 0 & 0 & \cdots \\ 0 & 1 & -1 & \cdots & 0 \\ 0 & 0 & \cdots & -1 & 0 \\ 0 & \cdots & 0 & 1 & -1 \\ \cdots & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$C = \begin{bmatrix} \frac{1}{C_n} & -1 & 0 & 0 & \cdots \\ 0 & \frac{1}{C_{n-1}} & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 & 0 \\ 0 & \cdots & 0 & \frac{1}{C_2} & 0 \\ \cdots & 0 & 0 & 0 & \frac{1}{C_1} \end{bmatrix}$$

Sisthemodeswitchstatevectorwhere1indicatesthehigh-sideswitchconductingand0thelow-sideswitchconductingforeachcellcomplementarypair. Equation(4)representstheloadcharacteristicandsobemodified torepresentothertypesofload.



and Vistheindividualcellcapacitorvoltagevectorand

Fig.3Inverterlegofflyingcapacitormultilevelinverter.

Theabovematrixrelationshipsgoverningtheflying-capacitorinvertercanbeincorporatedwithina simplefixedtime-steppingproceduretocalculatetheloadvoltage$v_o$andcurrenti_ow ithaparticular switchstate operated overaspecifictimeperiod.Bycombiningdifferentswitchstates operatedoverdifferenttime-periodsanyswitchingsequencepatterncanbesimulatedefficien tly.Thisfeatureisveryusefulforanalyzingtheinverter'soperati onwhensynthesizinga sinusoidusingafixedcontrol switchingsequence.Forexampleinathree-cell,single-phaseinvertertheAandCmatricesareasfollows:

$$A = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ 0 & 0 & 1 \end{bmatrix}$$

$$C = \begin{bmatrix} 0 & 0 & 0 \\ 0 & {}^{2}/_{C_c} & -1 \\ 0 & 0 & {}^{1}/_{C_c} \end{bmatrix}$$

where$C_c$isthebasic cellcapacitance.Bysolvingequations(1),(2)and(3)byiteration

,thecompleteoutputloadwaveformscanbefoundforagivens witchingmodeasdefinedbyS.

Thecapacitorvoltagescanbecontrolledintwoways.Eitherthe capacitorvoltagesandcurrentdirectionaremeasuredandanap propriate switchstateischosen to

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correctthecapacitorvoltageoranaturalbalancingschemeisused.Naturalbalancingscheme(whichmaintainsthesteadystatestabilityofthecapacitorvoltagesbyusingequal dutycyclesforeverypairofcomplementaryswitches.Thiscanbedonebyusingaspecialpulsewidthmodulation(PWM)scheme.)isdiscussedinsectionIII.

i.Measuringcapacitorvoltageandcurrentandchoosing switchstate:

Thismethodrequiresmeasuringallthevoltagesofthecapacitorbussesandthedirectionofthephasecurrent.Whenthe signoftheerrorofthecapacitorvoltages and thedirectionofthecurrentisknown,anappropriateswitchstateforthedesiredoutputvoltagecanbeassigned.Thiswaytheoutputvoltagecanbechosenateveryinstant, whilealwaysbeingsuretheerrorsofthecapacitor voltagesarecorrected.

TABLEISWITCHINGTABLE

unbalance			Switchstate(positivecurrent)		
C1	C2	C3	$-V_{dc}/4$	0	$+V_{dc}/4$
-	-	-	1000	1100	1110
-	-	+	1000,0001	1100,1001	1101
-	+	-	1000.0010	1010,0011	1110,1011
-	+	+	1000,0001	1001,0110	1011
+	-	-	0100	1100,0110	1110,0111
+	-	+	0100,0001	1100,0101	1101,0111
+	+	-	0010	0110,0011	1110,0111
+	+	+	0001	0011	0111

Table1isatablewiththeswitchingstatesforapositivecurrent,There isno choicewhenthe desiredoutputvoltageVanis+/−Vdc/2,sothisisnotinthetable.Foreverypossibilityofdeviation ofthecapacitorvoltages(+or−),aswitchstatecanbedetermined. Here1000meansS1isonandS2-S4areoff.Asimilartableisavailableforanegativecurrent.

3. SIMULATIONMODELAND MODULATIONTECHNIQUES

independentcapacitorsclampingthedevicevoltagetoonecapacitor

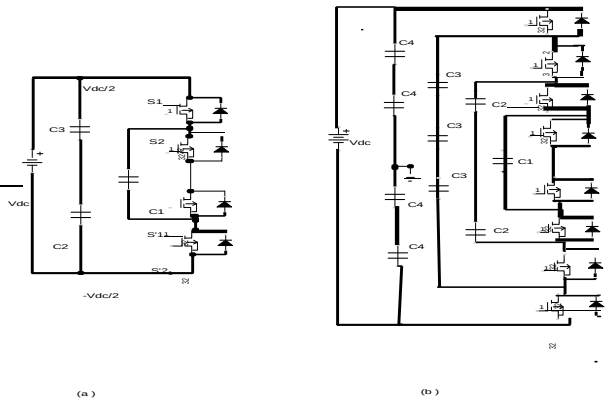

Fig.4Phase Legof (a)Threelevel FCMLI(b) FiveLevelFCMLI

voltagelevel.TheinverterinFig.3(a)providesathree-leveloutputacrossaandn,i.e$V_{an}=V_{dc}/2,0,-V_{dc}/2$.ForvoltagelevelVdc/2switchesS1andS2needtobeturnedon;for–Vdc/2switchesS'1andS'2andforthe0level, eitherpair (S_1,S_1^1) or (S_2,$S^1)_2$needstobe turnedon. Clamping capacitor C_1ischargedwhen$S_1$and$S_1$are turnedon,andis dischargedwhen S_2andS_2 areturnedon. ThechargeofC1canbebalancedbyproperselectionofthe0-levelswitchcombination.Fig.5showsMATLABsimulinkmodelfor3levelFCMLI.

InFig.4(b)showsAphase-legofa5levelflyingcapacitormultilevelconverter.Inthiscircuit,independentcapacitorsclampthedevicevoltagetoonecapacitorvoltagelevel.Thisconvertertopologyhasmoreflexibilitythanothermultilevelconvertertopologieslikethediode-clampedconverter.SwitchesS_1,S_2,S_3andS_4arecomplementary withthecorrespondingswitchesS^1,S^1, S_1 S_1 1 2

A) Flyingcapacitormultilevelinverteroperation:

Fig.3(a)illustratesthefundamentalbuildingblockofaphase-leg3-levelcapacitor-clampedinverter.Thecircuithasbeen calledtheflying capacitor inverterwith

$_3$ and S_4. Thevoltagesof thecapacitor banksareassumedtobe at thenominallevelat steady state.In Fig.4b,eachcapacitorsymbolassignsforthesamevoltagevalue.Sothefirstcapacitorbank(C_1)hasavoltageofV_{dc}/4,thesecond(2timesC_2)hasavoltageofV_{dc}/2,thethird(3timesC_3)hasavoltageof3V_{dc}/4andthefourthistheDC-busandhasavoltageV_{dc}.Thevoltageofthefive-levelphase-leg'a'outputwithrespecttotheneutralpointn,Van,canbesynthesizedbythefollowingswitchcombinations.Here,thementioned switchesareon,thecomplementaryareoff.

1. V_{an}=V_{dc}/2:turn on allupper switches,S_1,S_2,S_3andS_4.

2. V_{an}=V_{dc}/4:oneoftheupperswitchesisturnedoffanditscomplementaryisturnedon.Whenforexample$_2$isturnedon,V_{an} S^1 = V_{dc}/4 becauseof the following

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calculation:$V_{dc}/2$(of upper C_4's)−$3V_{dc}/4$(of C_3's)+$V_{dc}/2$(of C_2's).This way series connection of capacitors is made to create the desired output.

3. V_{an}=0V:now two upper switches are returned off and their complementary switches are turned on.A similar calculation as above can be made.

4. $V_{an}=-V_{dc}/4$:in this case,there is only one of the upper switches on.

5. $V_{an}=-V_{dc}/2$:turn on all lower switches,S^1,S^1, S^1_3 and S^1_4.

The voltage over the capacitors changes as current flows through the capacitors.By choosing an appropriate switch state for a desired output voltage according to the current direction,it is possible to control the voltage over the capacitors.

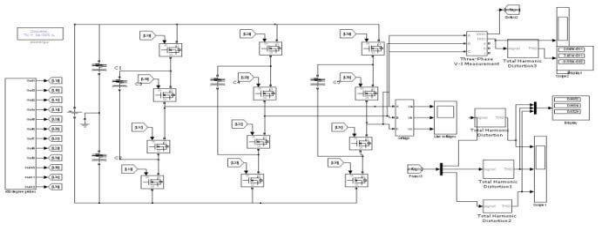

Fig.5.MATLAB Simulink model for 3 Level FCMLI

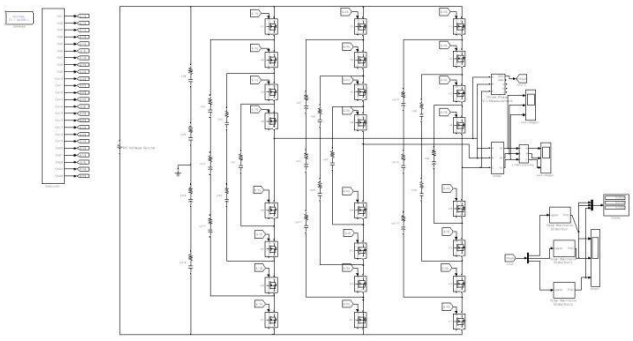

Fig.6.MATLAB Simulink Model for 5 Level FCMLI

B) PWM Methods for voltage balancing for flying capacitor:

Natural balancing of a flying capacitor multilevel converter is a technique which maintains the steady state stability of the capacitor voltages by using equal duty cycles for every pair of complementary switches. This can be done by using a special pulse width modulation (PWM) scheme.In this scheme,every pair of switches has a carrier sig carriers,the switch state of the corresponding switch pair is defined.When the reference signal is above the carrier,the upper switch is on and when below,the lower switch is on.

Controlling mechanisms for multilevel voltage source inverter can be classified into PWM and stepped techniques.PWM scheme consist of close loop and open loop modulations.Sinusoidal PWM,SVM and sigma-delta modulation are three main controls chemes of open loop modulation.Figure.7.shows the classification of modulation strategies for MLIs.

In this paper we consider carrier based pulse width nal which has a 90 degrees phase change,a so called phase shift carrier PWM (PSCPWM).When a reference signal,normally the desired output voltage,is compared with the

modulation(CBPWM).CBPWMhasitselfthreebranchesnamely:In-PhaseDisposition(IPD),AlternativePhaseOppositeDisposition(APOD)andPhaseOppositeDisposition(POD).Although,SVMdirectlycontrolsline-to-linevoltagesoftheinverter,allofCBPWMsubtechniquescontroleachphaselegofinverterseparately.

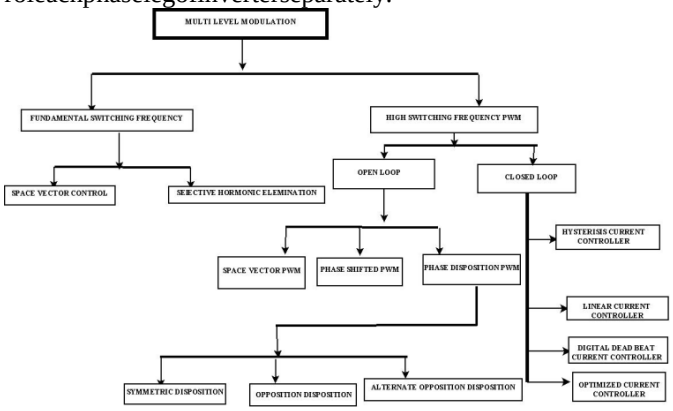

Figure.7.ClassificationofmodulationstrategiesforMLIs

Inthiscaseforthenlevelflyingcapacitorthen-1carriersignalsarephaseshiftedby$T_P/(n-1)$.Fig.8presentsthecarriersignals,modulatorsignalandconnectionfunctionsforfivelevelcapacitorflyinginverterforonele g.Inthiscasethereare four carrier signals:

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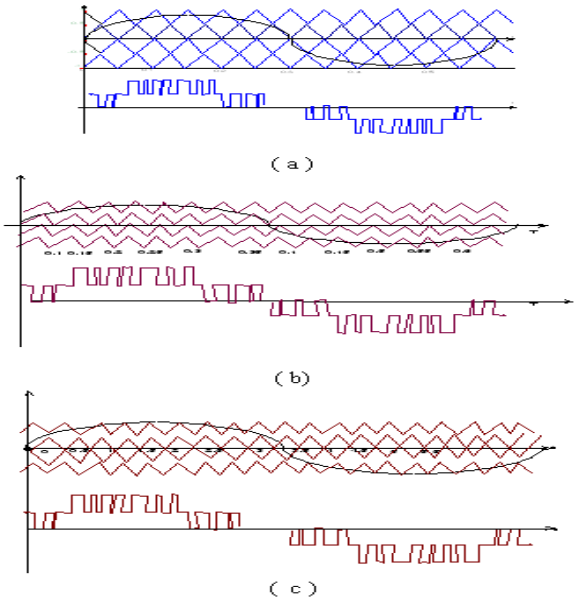

Fig.8.DifferentModulationsub-techniquesandrelativeinverteroutputvoltagewaveform:(a)APOD,(b)IPD,(c)POD

SpacevectorPWMwaveformshavesome advantages suchaseaseofdigitalcontrolandswitchingwaveformoptimization.FromFig.9,SVMidentifieseachswitchingstateasapointincomplex(α,β)space.Areferencephasorrotatinginthe(α,β)planeatthefundamentalfrequencyissampledwithineachswitchingperiod,andthethreenearestvectorsareselected.Dutycycleofeachvectorcanbecalculatedbythetimeaverageprinciple:

$$T_1U_1 + T_2U_2 + T_3U_3 = T_sU^*$$
$$T_1 + T_2 + T_3 = T_s$$

whereT1,T2andT3aredutycyclesofU1,U2andU3,respectivelyandTsistheswitchingperiod.Inmultilevelinverters,morethanoneswitchingstateisavailableformediumvectors.Forinstance,thespacevectorofAinFig.4hasfourdifferentswitchingstateswhichare[-E,-2E,-2E],[0,-E,-E],[E, 0,0],and[2E,E,E].

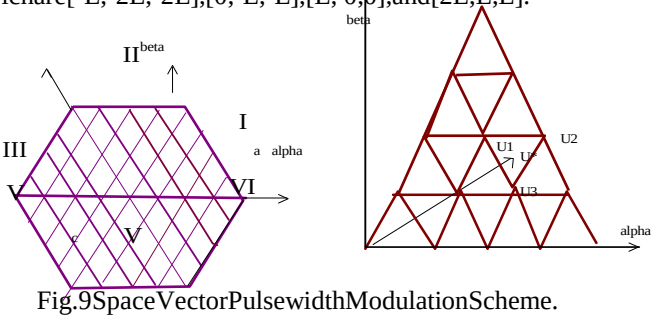

Fig.9SpaceVectorPulsewidthModulationScheme.

4. SIMULATIONRESULTS

TheCBPWM(IPD,APOD,POD),methodspresentedaboveareanalyzedwithrespecttotheirharmoniccontentandtotalharmonicdistortionfactor(THD)for3leveland5levelFCMLI.Basefrequency=$\omega_B=2\pi f1 = 2^{\times 3.14 \times 50 = 314}\frac{rad}{sec}$.
Carrierfrequency=f_{cr}=1000hz.

TableIIIFCMLC(5L)ComponentSpecifications

Numberofmainswitches	36
DeviceONresistance	0.01Ω
DeviceOFFresistance	1.0E6Ω
Forwardvoltagedrop	0v
ForwardbreakoverVoltage	0.2KV
ReversewithstandVoltage	0.2KV
Snubberresistance	500Ω

Outputwaveformofthreelevelinverterandharmonicspectrumshowninfig10to13.

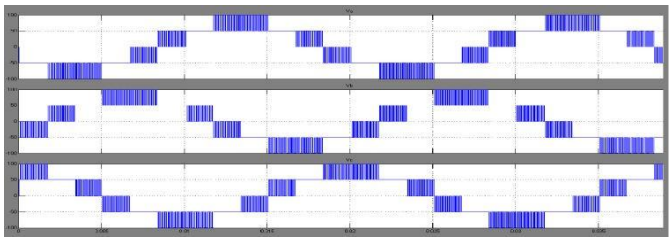

Fig.10.Outputvoltagewave formfor3-LevelFCMLI

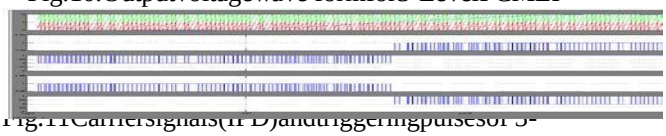

Fig.11CarrierSignals(IPD)andtriggeringpulsesof 5-LevelMLI

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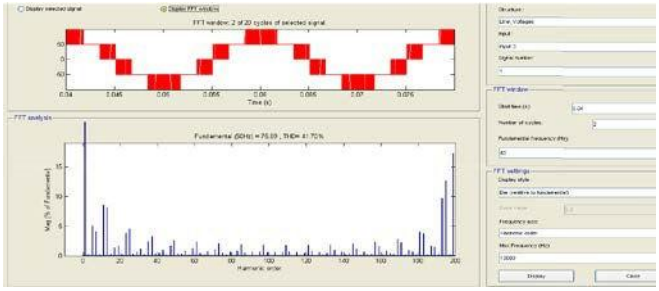

Fig.12Phasevoltageandfouriercomponentsforthreelevelf lyingcapacitorinverterwithphaseshiftedcarriersignals.(A POD)

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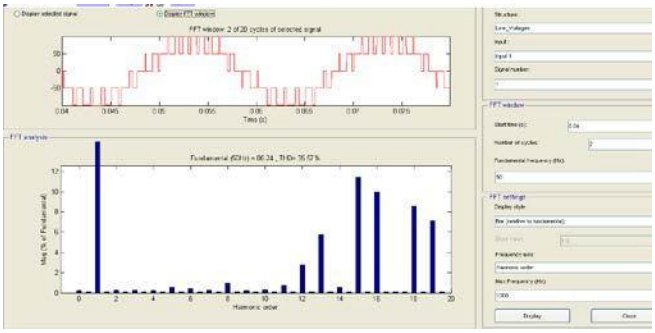

Fig.13Phasevoltageandfouriercomponentsforthreelevelf lyingcapacitorinverterwithphaseshiftedcarriersignals.(P ID)

Outputwaveform offivelevel inverterandharmonicspectrumshowninFig14to16.

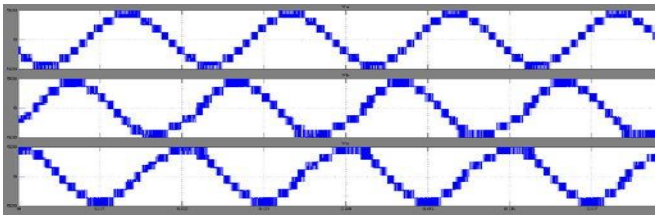

Fig.14.Outputvoltagewave formfor5-LevelFCMLI

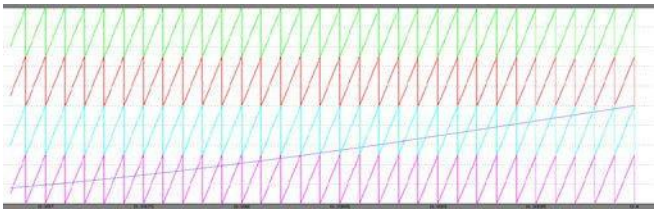

Fig.15Carriersignals(IPD)5-LevelMLI

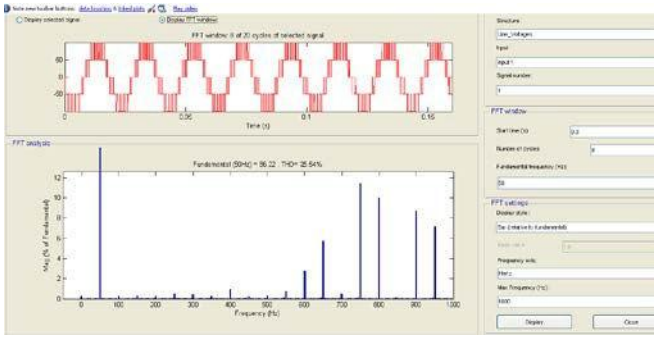

Fig.16Phasevoltageandfouriercomponentsforthreelevelf lyingcapacitorinverterwithphaseshiftedcarriersignals.(P ID).

TABLEII%THDOF THREELEVELWITHIPDANDAOPD

ThreeLevelFCMLI	IPDModulation %THDofoutput Voltage			AOPDModulation %THDofoutput Voltage		
	Ph-A	Ph-B	Ph-C	Ph-A	Ph-B	Ph-C
ma=1, fm=50 Hzfcr =1000 hz	35.6%	36.94%	34.23%	39.34%	41.66%	40.12%
ma =0.8 fm=50 Hzfcr =1000 hz	35.9%	38.43%	37.35%	41.21%	43.01%	40.59%

TableIIgivesthe%THDvaluesofthreelevelFCMLI withIPDandAOPDmodulation.Insummary,theIPDmodulatio nproducesbetterharmonicprofilethantheAPODmodulation.a ndTableIIIsummarizethe%THDvaluesforthreeLevelFCMLI andfiveLevelFCMLIwithIPDmodulation.Fig17showsgraphf or%THDvaluesofthreelevelandfivelevelFCMLIswithrespect ivecarrierfrequencies.

TABLEIII%THDOF THREELEVELANDFIVELEVELFCML IWITHIPD

IPD Modulation	ThreeLevelFCMLI			FiveLevelFCMLI		
ma=0.8 Fm =50 Hz Fcr	Ph-A	Ph-B	Ph-C	Ph-A	Ph-B	Ph-C
	35.9	38.43	37.35	23.12	26.25	25.42

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=1000 hz						

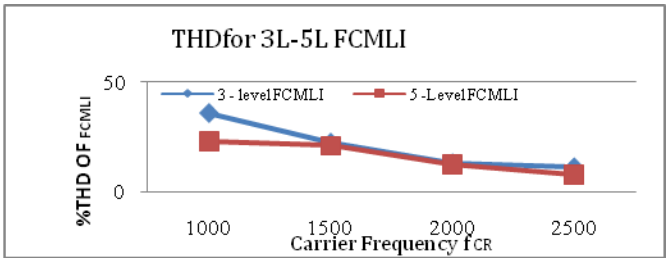


Fig17%THDvaluesofthreeleveland fivelevelFCMLIswithrespectivecarrierfrequencies

TheTHDarecalculatedforthefirst200harmonics.The modulation index is 1andswitchingfrequency is 1000Hz.Three-phasereferencesignalsareobtainedbyaddingtheoffsetvoltage Vofftotheoriginalphasevoltagestoobtainanequivalentreferencevoltage.Theoffsetvoltageisdefinedas:

$$V_{off} = -\frac{[\max[(V_a^* + V_b^*] + V_c^*) + \max[(V_a^* + V_b^*] + V_c^*)]}{2}$$

TheTHDvaluesobtainedbysimulationusingthepresentedmodeloftheinverterforthreeandfivelevelflyingcapacitorinverterforphaseshiftedPWMmethod(PSPWM), FromFig.12,13and16wecanseethattheharmoniccarrierbands appearatfrequenciesfhgivenby:

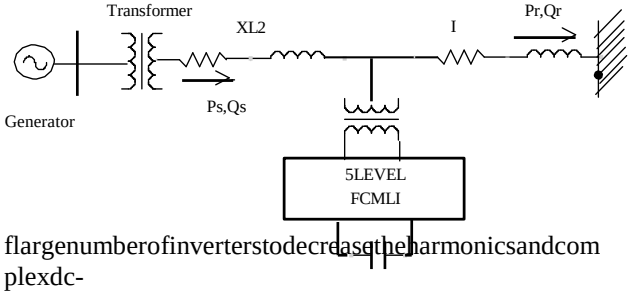
$$f_h = k\,(n-1)f_p$$

where'k'isaninteger(k=1,2,3...),f_p isthefrequencyofcarriersignalandnisthenumberofinverterlevels.

5. APPLICATIONSOFFCMULTILEVELIN VERTERSIN POWERSYSTEMS

ThemainApplicationsofFCMLIareFACTS(staticsynchronouscompensator(STATCOM),staticsynchronousseriescompensator,unifiedpowerflowcontroller(UPFC))andPowerLineconditionerorActivePowerFilters(APF). Atpresent,therearethreebenchmarkmultilevelinvertertopologies:i)diode-clampedmultilevelinverter(DCMLI), ii)cascadeH-bridgeinverter,andiii)flyingcapacitormulti-levelinverter(FCMLI).DCMLIsuffersfrom thelimitationsofdc-linkvoltageunbalance,indirectclampingoftheinnerdevicesandmultipleblockingvoltagesoftheclampingdiodes.H-bridgecascadeinverterhaslimitationssuchas,therequirementoaback-to-backarrangement(e.g.,inUPFC)isnotpossiblebecauseashort-circuitwillbeintroducedwhentwoback-to-back convertersare notswitchingsynchronously .Inthisinverter,theswitchingmodulationneedstobeoptimizedforhighperformanceapplicationsduetoalimitedcombinationofswitchingpatterns.Moreover,forreactivepowerexchange,thepowerpulsationattwicetheoutputfrequencyoccurringwiththedc-linkofeachH-bridgeinvernecessitatesover-sizingofthelinkcapacitors.

TheFCMLIattemptstoaddresssomeofthelimitationsimposedbytheabove-mentionedinverters.Withtheincreaseinthenumber ofoutputvoltage levels, thenumberofdc-link



flargenumberofinverterstodecreasetheharmonicsandcomplexdc-voltageregulationloop.Itneedsseparatedcsourcesforrealpowerconversionandthushassomewhatlimitedapplications. Connectingseparatedcsourcesbetweentwoconvertersin

Fig.18(a)STATCOMcompensatedsinglemachineinfinitebussyst em.

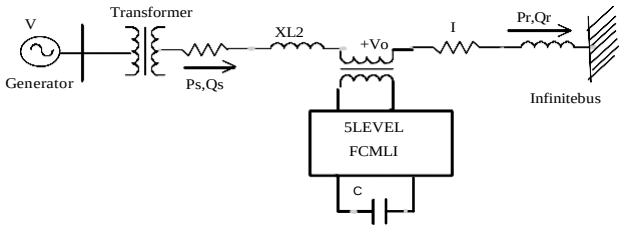


Fig.18.(b)SSSCcompensatedsinglemachineinfinitebussystem

capacitorsincascadeandinDCMLIincreaseandhencetheircontrol becomemorecomplexespeciallyintransientconditions.However, thedc-capacitorcontrolloopinFCMLIisassimpleasintheconventionaltw o-levelinverterand isindependentofthenumber ofoutputvoltagelevels.

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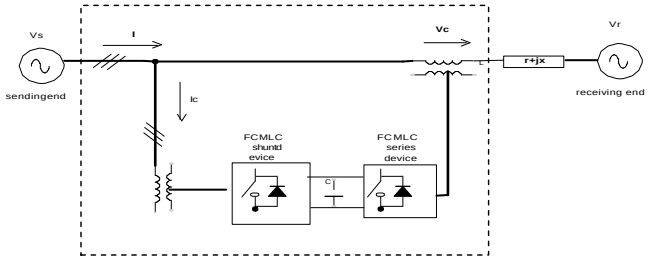

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Fig.18(c)SysternconfigurationofaUPFCbasedon FCMLI

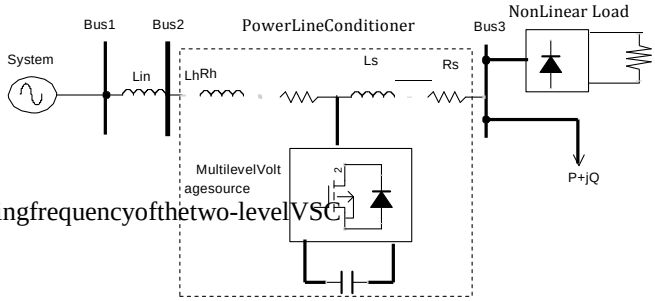
ThetypicalstructureofFCMLImakesitpossibletosplitthevoltage constraintsandtodistributethemonseveralswitchesofsmaller ratingsinseries.Thisalsomakesitpossibletoobtainasignificanti mprovementoftheoutput waveformandtoincreasetheapparentfrequencyofthis wave,allowingasignificantreductionofthefilteringrequireme nts.Theuseofcapacitorsforthevoltageclampinginsteadofdiod esasinDCMLI,permitsseveralswitchcombinationsforapartic ularvoltagelevelgeneration,whichmaybeusedforpreferentialc harginganddischargingofcapacitors.

Thecontrolstrategyusesinherentfeature ofFCMLIandissufficienttohavebalanceddcvoltagesoftheflyi ngcapacitorsifthevoltageofthemaindcbuscapacitorisbalance d.Therefore,acomplexdccapacitorvoltagecontrolloopisnotre quiredinanFCMLI-basedFACTScontrollersandindependentcontroloftheoutputv oltageandflyingcapacitorvoltagescanbeachieved.EventhoughtheFCMLIoffersvariousfeatures,extensiveresearcheshaven otbeenreportedonitspotentialFACTSapplications.Fig.18showssinglediagramsforFCMLIbased(a)STATCOM(b)SSSC(c)UPFC.

Itisprobablyduetosomeofitslimitationssuchasrequirementsof largenumberofcapacitorsandtheirefficientcontrol.Someresea rchessuchashavereportedcontrolschemesforbalancingtheflyi ngcapacitorvoltages,whichusePIcontrollersforeachflyingcap acitorvoltagebalancing

Itisprobablyduetosomeofitslimitationssuchasrequirementsof largenumberofcapacitorsandtheirefficientcontrol.Someresea rchessuchashavereportedcontrolschemesforbalancingtheflyi ngcapacitorvoltages,whichusePIcontrollersforeachflyingcap acitorvoltagebalancing.

Inindustrialordistributionsystemapplicationswherevoltagera ngesfrom4.16to13.8kV,eitherlargereactorsoraveryhighswitc hasto be employed tomeetsystemharmonicrequirements.Inthefirstcase,sincether eactorsareinserieswiththeload,intolerablevoltagedropwillbec ausedbythereactors.Veryhighswitchingfrequencycannotbea chievedduetotheswitchingspeedlimitofhigh-voltagehigh-powerdevices.Toresolvetheproblemsstatedabove,aflying-capacitormultilevelVSC is employed.Phase-shiftsinusoidalPWM(SPWM)switchingconceptisadoptedan dappliedtocontroltheswitchesofthisconverter.Theabilityofba lancing



hingfrequencyofthetwo-levelVSC

Fig.19singlelinediagramforFCMLIbasedpowerline conditioner.

unbalancedloadispossibleinadditiontothereactivecompensationandharmonicsuppressioncapabilities.Duetotheswitchingscheme,theresultantoutputvoltageofthismultilevelVSChasaveryhighequivalentswitchingfrequency,evenifthesswitchingfrequencyoftheindividualswitchesis notvery high.As aconsequence,thevaluesofthereactorsarelow.ThusReactivePowerCompensation,HarmonicSuppression,BalancingUnbalancedLoadpossiblebyusingFCMLI.TheSchematicforpowerlineconditionerbyusingFCMLIShowninFig19.

6. CONCLUSION

Inthispaper,flyingcapacitormultilevelinverterFCMLIswithIPDandAPODmodulationschemesarestudiedindetail. Thetheoreticalanalysis,design,andSimulinkimplementationofflying-capacitor multilevelconvertersof3rdand5thlevelarepresented.Thesimulationresultsalongwith FFTanalysisforlinevoltagepresentedandcomparedamongvariouslevelsofFCconverters andmodulationschemesfordifferentmodulationindexm_a, carrierfrequency$f_c$andfrequencymodulationindexm_f.ApplicationsofFCMLIinpowersystemsaresummarized.

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